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The floodlighting of Buckingham Palace during the Celebration of the Silver Jubilee of His Majesty The King.

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VOL. VI. AUGUST, 1935. No. 3.

The Design of Lighting Fittings for "Osira" Lamps.

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With the development of the "Osira" lamp the quantity of light which could be produced for a given energy consumption was increased to nearly three times that obtained with the tungsten filament lamp. This was an achievement welcomed alike by the engineer and the user of light. But the story is not all told in these few words. The new method of light production involved a new form of light source and in his endeavours to utilise the more efficiently generated light, the illuminating engineer was faced with new problems. What follows is a description of the lighting requirements of the first fittings for the new lamps, of the optical designs employed and of the results obtained.

IT was with some misgivings that work was begun on the design of fittings for "Osira"* high pressure mercury vapour lamps. Although the virtues of the hypothetical point source had long since been shown to be mythical, (except where there is need for the hypothetical parallel beam from the mathematical paraboloid), the first "Osira" lamp, with a column of light over six inches long looked a little unpromising. This was the form in which the physicist handed the first of these new light sources to the illuminating engineer.

It would have been all too easy to lose much of the gain in efficiency over the filament lamp by inadequate fittings design. That this did not happen is borne out by the wide and successful application of the new lamps since the first installations in 1933.

LIGHTING CHARACTERISTICS OF THE "OSIRA" LAMP.

The first high pressure mercury vapour "Osira" lamp to be developed had a rating of 400 watts. In this 400-watt lamp the effective light source was a cylindrical cord of light $6\frac{1}{4}$ inches long and approximately $\frac{1}{4}$ inch in diameter, a radical change from the gasfilled filament lamp. These dimensions still apply to the 400-watt lamp although its efficiency has been much increased above that of the early types. The cord is not uniformly bright throughout its width, having, as might be expected, a greater brightness at the middle than at the edges. But this distribution of brightness is of secondary importance in a source whose width in any case is small. To the fittings designer the characteristics of primary importance in a source are its overall dimensions and its light distribution. The dimensions have already been given and the distribution is shown, for a plane containing the axis of the source, in fig. 1.

If the lamp axis is assumed vertical (the most usual position and in fact the only position in which the lamp can safely be burned without a magnetic deflector), the curve shown is that in any vertical plane.

The candle-power values are appropriate to a lamp giving the present day rated initial output of 17,000 lumens or having an efficiency of 42.5 lumens per watt. The installation designer may be interested

* *Registered Trade Mark.*

in the way in which the lamp light output is maintained throughout life. A safe figure to take for the average efficiency throughout the nominal 1500 hours life is 35 lumens per watt.

The shape of the polar curve follows from the shape of the source. The intensity is a maximum horizontally, in which direction the projected area of the source is a maximum and decreases regularly to a minimum vertically downwards and upwards. This is a second radical difference between the filament lamp and the "Osira" lamp from the point of view of design.

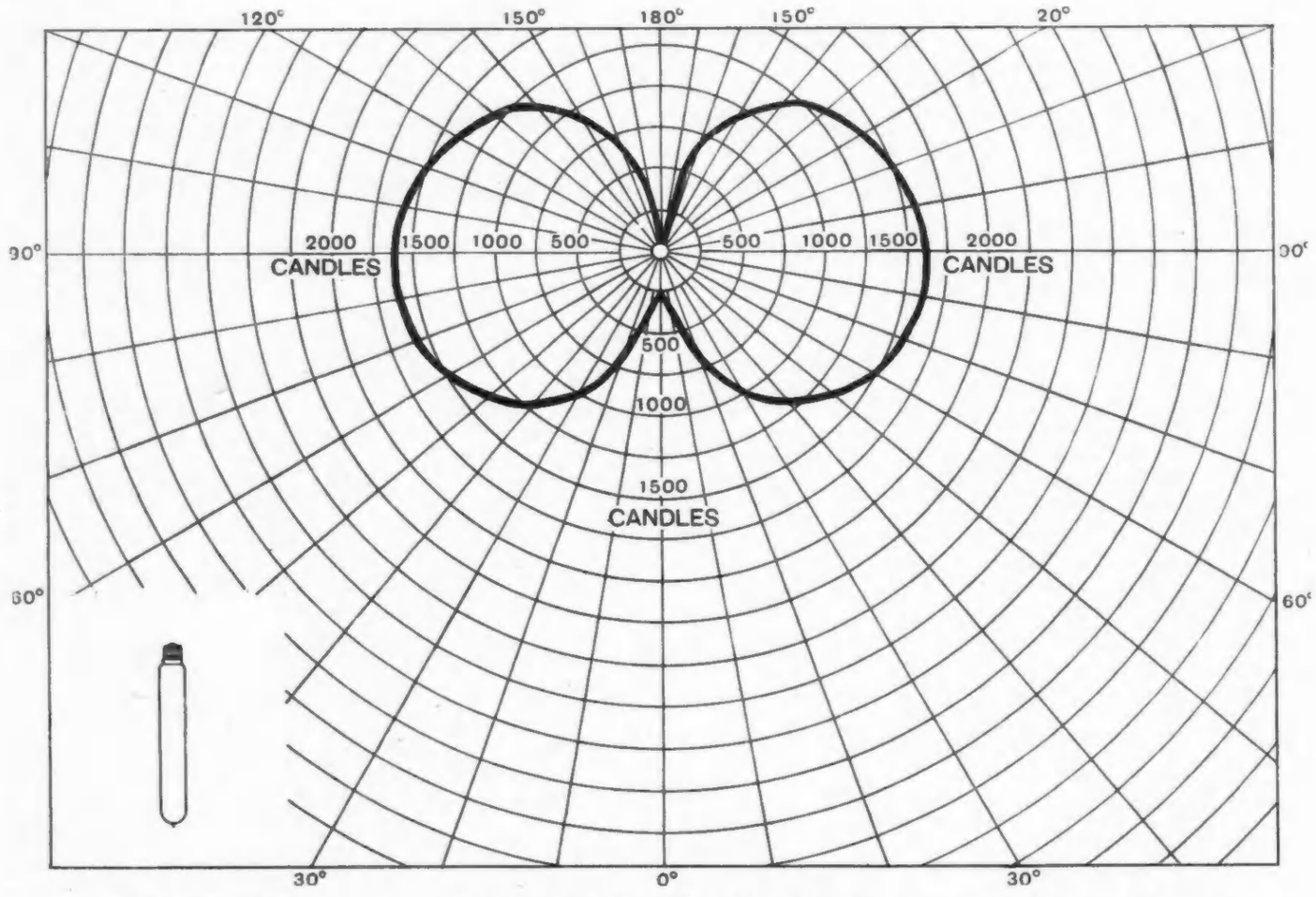


Fig. 1.—Polar curve showing light distribution in a vertical plane from 400 watt "Osira" lamp. Light output, 17,000 lumens.

A second lamp of the "Osira" type, but having a rating of 250 watts, was introduced in September of last year. In this lamp the light column is three quarters of the length ($4\frac{3}{4}$ inches) and approximately three quarters of the width of that in the 400-watt lamp. The brightness of the column is closely the same in the two cases so that the intensity of the smaller lamp in any direction is reduced approximately in the ratio of the projected areas *i.e.* $0.75^2 = 0.56$. Actually the rated initial efficiency of the smaller lamp is rather lower than that of the 400-watt lamp, viz. 36 lumens per watt, so that the initial light output is 9,000 lumens, slightly less than 0.56 times the output of the larger lamp. On account of the similarity in shape between the light sources in the two cases, they have a similar form of light distribution and the intensity values for the 250-watt lamp can be obtained from the curve in fig 1 by multiplying the ordinates by 0.53. The maintenance of efficiency thoughout the nominal 1,500 hours life is even better than that of the 400-watt lamp.

One further item of information is necessary for the practical designer—dimensional particulars which give the light centre length and overall size of the lamp. For the two lamps under consideration these are given in fig. 2.

	250 watt	400 watt
A	290 ± 10mm.	325 ± 15mm.
B	50mm	50mm
C	177 ± 13mm.	190 ± 8mm.
D	120 ± 5mm.	160 ± 5mm.

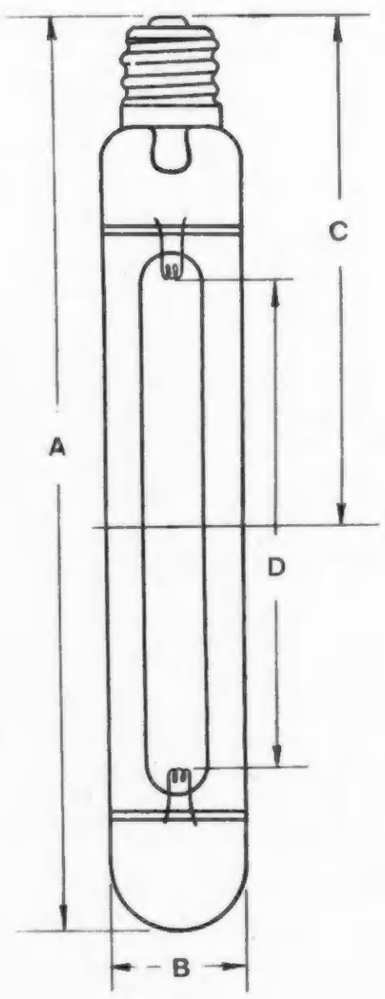


Fig. 2.—Dimensions of "Osira" lamps.

INDUSTRIAL UNITS FOR "OSIRA" LAMPS.

If the requirements of the majority of general lighting installations in industrial situations are analysed, it will be found that fittings giving three

main types of light distribution fulfil most of the needs. The first should have a wide distribution making it suitable for large space lighting whether interior or exterior where not very high illumination is required and where the shadows caused by having only a few fittings are not likely to be detrimental; the second should have a complete cut-off of the light source at an angle of 20° below the horizontal, so as to comply with the Home Office recommendations with regard to avoidance of glare and yet have as wide a distribution as possible. The third should be suitable for mounting on the side walls of interiors or exteriors and give a wide distribution about an axis at 45° to the vertical.

It will be seen from the polar curve in fig. 1 that the bare "Osira" lamp has inherently a wide spread distribution but that the intensities at or near the downward vertical are very low. Little more was required from the first type of fitting therefore than that it should fill up the hollow in the lower part of the bare lamp curve, so as to avoid dark areas under the unit, but without reducing to an unnecessary extent the intensity of the bare lamp at angles approaching the horizontal. It proved possible to make such a unit on simple lines from one of the most

Fig. 4.—Distributing type "Osira" industrial reflector unit.

serviceable materials for the construction of industrial reflectors—vitreous enamelled steel. This material is commonly employed because the steel blank can be spun or pressed into a variety of shapes before enamelling, the enamelled surface is durable and easily cleaned and has a reflection factor of about 75 per cent. But for the unit under consideration it had the further advantage of a glazed surface. This surface glaze reflects only about 7 per

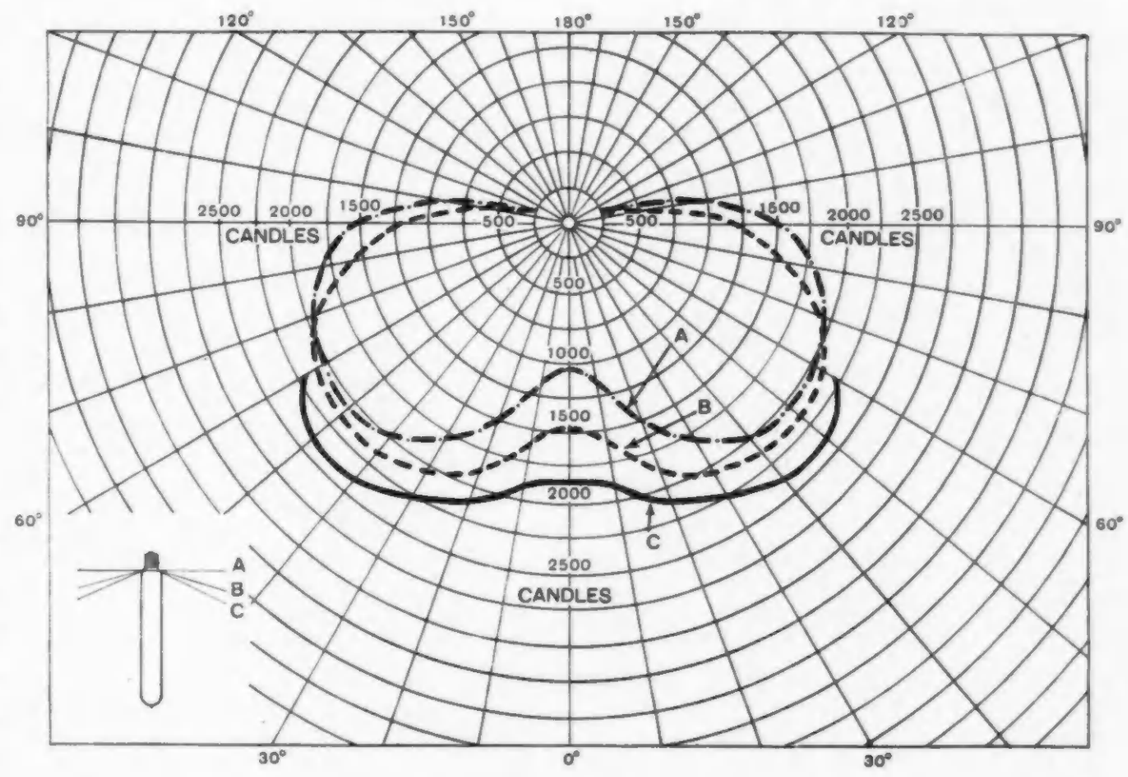


Fig. 3.—Polar curves showing light distribution in a vertical plane from experimental reflectors and an "Osira" lamp. A—90° semi-vertical angle; B—77° ditto; C—70° ditto.

cent of the light incident upon it, but this is regularly reflected as from a polished mirror so that the direction of reflection can be controlled by the shape of the reflector and light can be directed accurately into angles in which it is required. The main component of the reflection from the enamel, as distinct from that from the surface glaze, is diffusely reflected which means that the intensity of reflected light in any direction depends only on the projected area of the reflector and whilst therefore a general redirection of light below the horizontal is possible, the bare lamp intensity cannot be augmented in a narrow angle. With the reflector under consideration, the maximum concentration of light was required vertically downwards to compensate for the low intensity of the "Osira" lamp in this direction and the component reflected from the surface glaze of the enamel was needed for this purpose.

Distributing Unit.

By making the reflector in the form of a simple cone, a considerable proportion of the small amount of light specularly reflected by the polished surface of the enamel can be concentrated into a narrow angle. With a reflector of this form the maximum intensity occurs in the direction of the axis of the cone and the concentration falls off as the angle from the axis becomes greater. It is possible by a suitable design of the reflector so to augment the intensities from the bare lamp in this way, that the intensity under the unit is substantially uniform. The precise form of the concentration from the reflector will

depend on the angle of the cone and the best shape for the reflector was found after a series of experiments with conical reflectors of various angles and of the maximum reasonable diameter. The forms of the polar curves from three 22 inch diameter experimental units are shown in fig. 3. It will

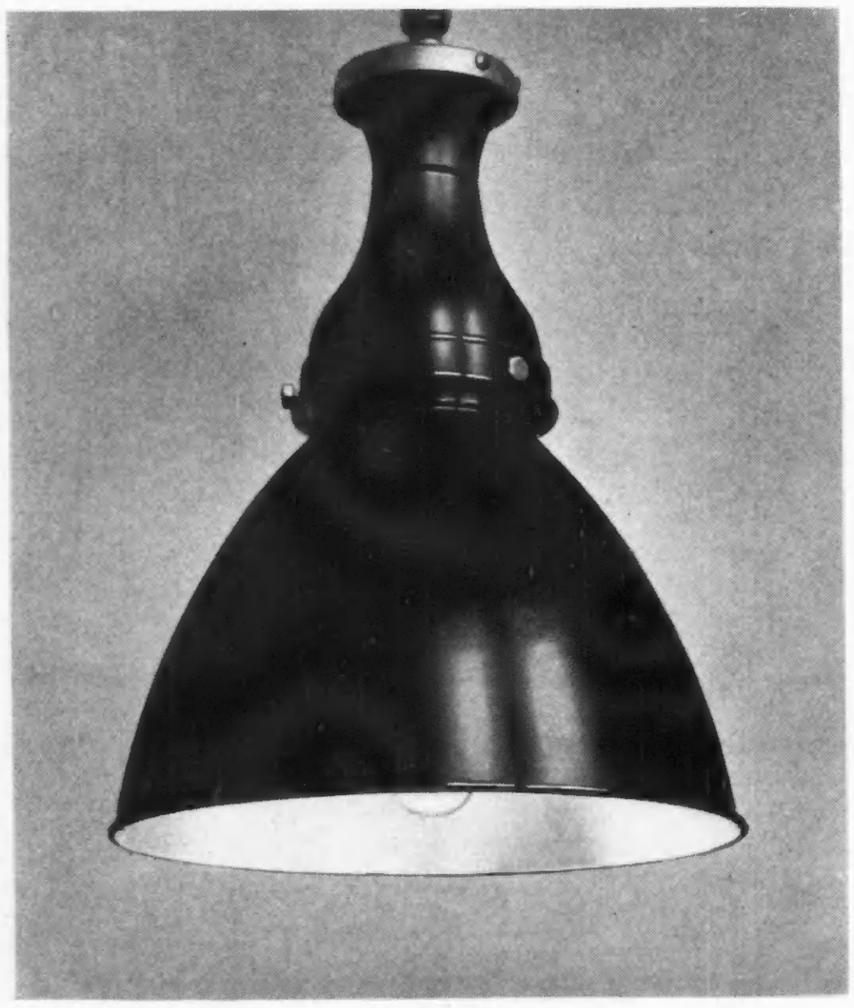


Fig. 5.—Dispersive type "Osira" industrial reflector unit.

be seen that the 70° cone gives the best results. Cones of greater angle give insufficient intensity downwards, and cones of less angle too high an intensity. The final design of unit, shown in fig. 4, was therefore based on the 70° cone.

Dispersive Cut-off Unit.

In the design of the dispersive cut-off type unit, the natural tendency for the light from a long source to be concentrated along the axis of a deep reflector becomes a difficulty. It is desirable in this case that the unit shall have the widest possible distribution consistent with a complete cut-off of the light source at an angle of 20° below the horizontal. The design was begun as usual from the top of the reflector, and the minimum diameter and position of the neck of the unit were determined by the requirement that this should be interchangeable with the conical reflector. The upper parts of the contour were designed so that the light specularly reflected from the enamelled surface should not be reflected in directions parallel with the axis of the lamp and also so that as little of it as possible should have to pass through the lamp. Lower down the contour, light was reflected at as high an angle as possible consistent with not passing through more of the lamp than was necessary, and emerging from the reflector after only one reflection. This reflecting scheme was continued until the lower edge of the reflector reached the 20° cut-off line.

One further check had to be made before the unit was constructed. This was to ensure that the reflector was of such size that the surface brightness of the enamel would not be materially in excess of 5 candles per square inch. It is nowadays agreed that any surface having a brightness below this figure and coming within the normal field of view does not produce discomfort. The unit as finally constructed is shewn in fig. 5. The light distribution produced, as will be seen from fig. 6, proved wider than that associated with the dispersive reflector for filament lamps in spite of the greater dimensions of the "Osira" source and the rigid cut-off requirements.

Angle Unit.

The third, angle reflector shewn in fig. 7, resulted from the direct application of a filament lamp reflector which had given satisfactory results. The extra dimensions of the "Osira" source in this case were of little importance and the resulting distributions as shewn in fig. 8 are comparable in shape with those from a filament lamp unit, but for equal wattage lamps have ordinates two and three quarter times as great.

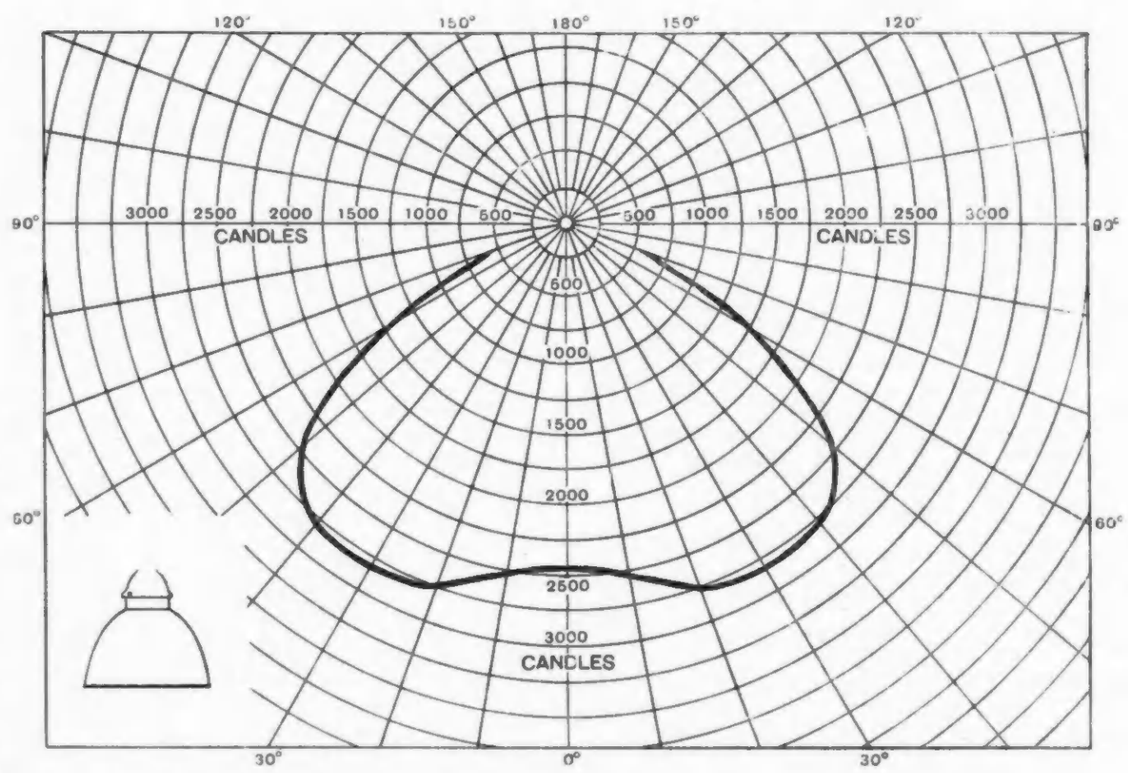


Fig. 6.—Polar curve showing light distribution in a vertical plane from dispersive type industrial unit with a 400 watt "Osira" lamp.

Modifications for Exterior Use.

The small bulb of the "Osira" lamp operates at a temperature sufficiently high for it to need protection from rain splash if cracking is to be avoided. The reflectors described above are of insufficient size to protect the lamp adequately, and if the units are to be used outdoors, some further safeguard in the

form of a well-glass round the lamp is necessary. It is desirable that this well-glass should have the minimum possible diameter as it must be fixed on the lantern top and the reflectors must pass over it. The glass diameter thus controls the diameter of the central hole in the reflectors and it is desirable that this should be a minimum. The well-glasses for the outdoor industrial fittings were therefore designed to have the minimum possible diameter consistent with a temperature at which they themselves would be safe from cracking by rain splash. From the connection between the maximum temperature of the well-glass and its diameter, determined experimentally (see fig. 9) it was possible to choose the optimum dimensions. Thermal endurance tests had suggested 200°C as a safe operating temperature for the heat-resisting glass to be used and from fig. 9 it will be seen that the minimum diameter of well-glass possible with a 400-watt lamp is 6 inches. Similar tests on the 250-watt lamp gave a figure of 4 inches for the smaller units.

Samples of the glassware in these diameters were finally subjected to an artificial rainstorm in the open air after burning for two hours and the results confirmed the expectation that the units would be satisfactory under practical operating conditions.

As shown in fig. 10 the well-glass screws into a copper ring and any of the reflectors can be fixed over it and attached to the cast top.

STREET LIGHTING UNITS.

It is in street lighting that the "Osira" lamp has found its principal application. This is understandable, for the light output of the first lamps was approximately equal to that of the 1000-watt filament lamp and in street lighting where so much has to be lighted with so little light, the gain in efficiency was of the utmost value.

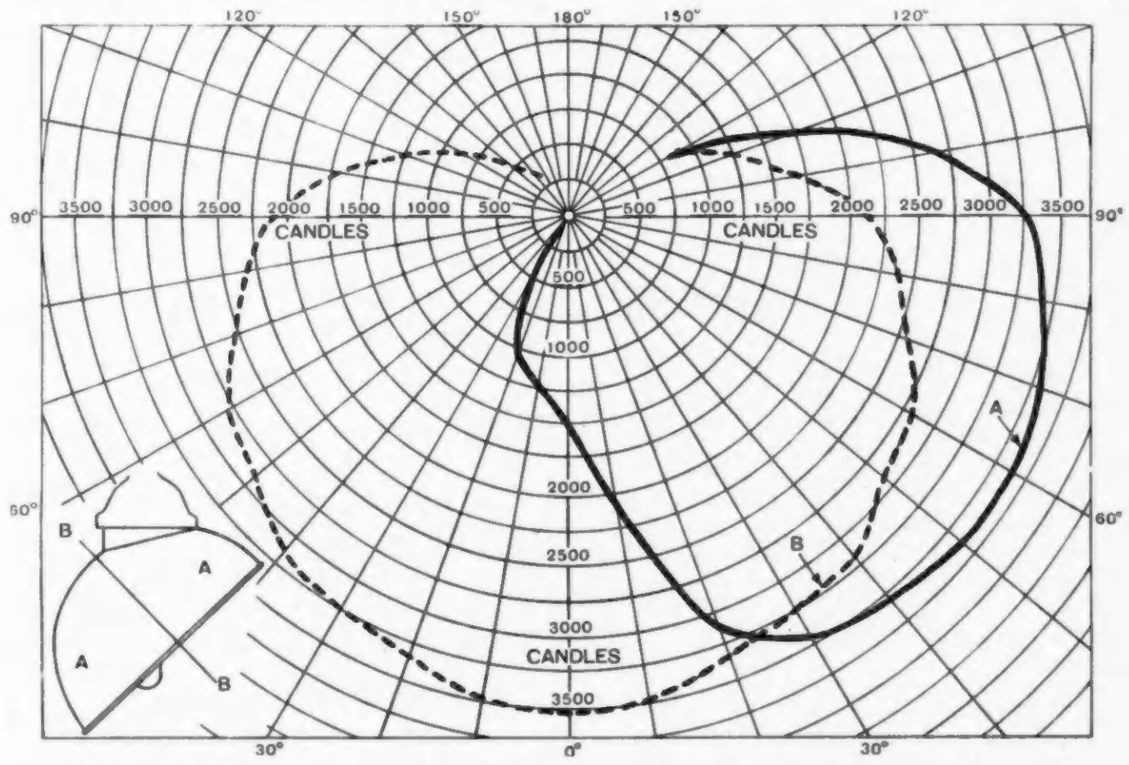


Fig. 8.—Polar curve showing light distribution from 45° angle type industrial unit with a 400 watt "Osira" lamp.
A in plane AA (plane of paper for small sketch).
B in plane BB (see small sketch).

Street lighting units can be divided broadly into two classes—those from which the light distribution is symmetrical and those from which it is asymmetrical. The former are required for the lighting

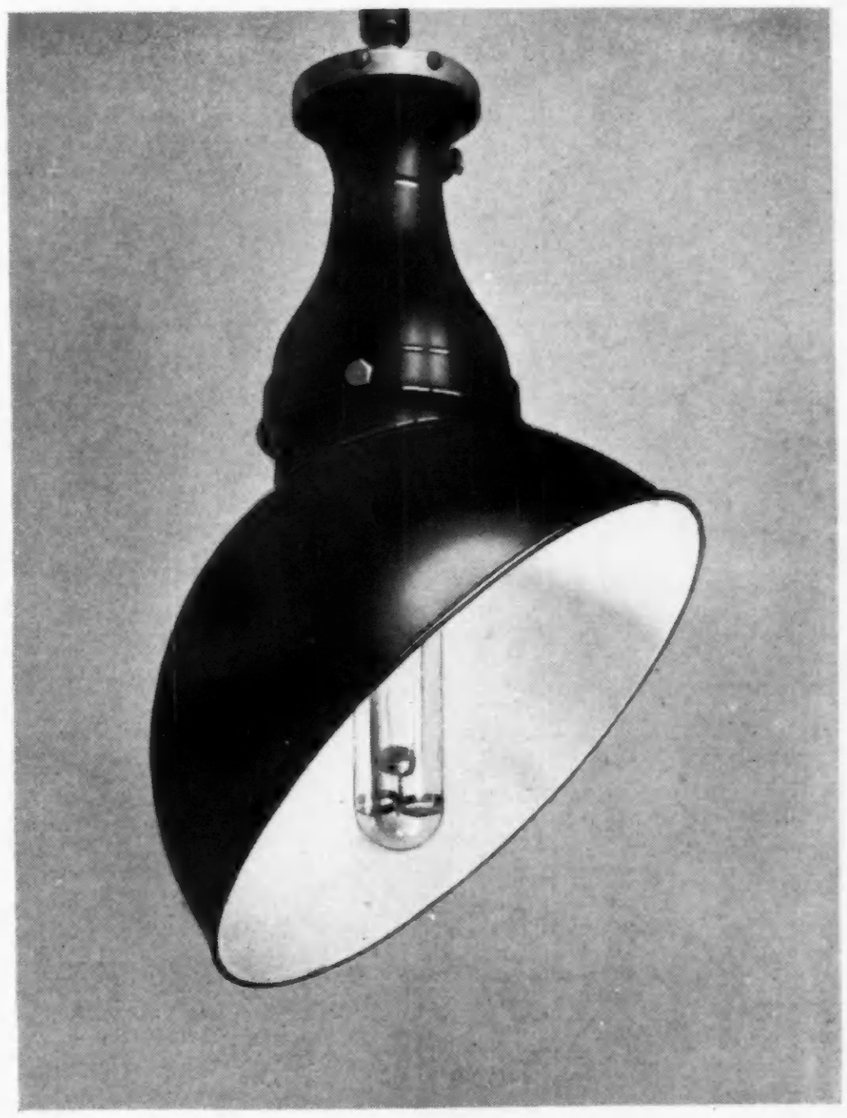


Fig. 7.—45° angle type "Osira" industrial reflector unit.

of wide roads, intersections and open spaces, whilst the latter are required for normal road lighting where the carriageway is of the order of 30 ft. wide and the posts from 100 ft. to 200 ft. apart. A requirement of all street lighting distributions is that they should produce as large an area as possible of effectively bright road surface and that there shall be no shadows or dark regions visible.

Experiment and practical experience have both shown that the best road appearance is usually obtained from a distribution in which the intensities increase steadily from vertically below the unit to a maximum value at an angle between 60° and 85° to the vertical (according to the specific purposes of the fitting). The bare lamp provides little light vertically downwards, while its maximum intensity is directed horizontally. Considerable redirection of the light has therefore to be effected, and with the new shape of source novel methods had to be adopted. Two types of unit giving a symmetrical distribution have been developed, and four units to give an asymmetrical distribution.

Symmetric Fittings.

Of the symmetric types the first redistributes the light by diffusion and the second by reflection. In the former the whole of the outer globe (which

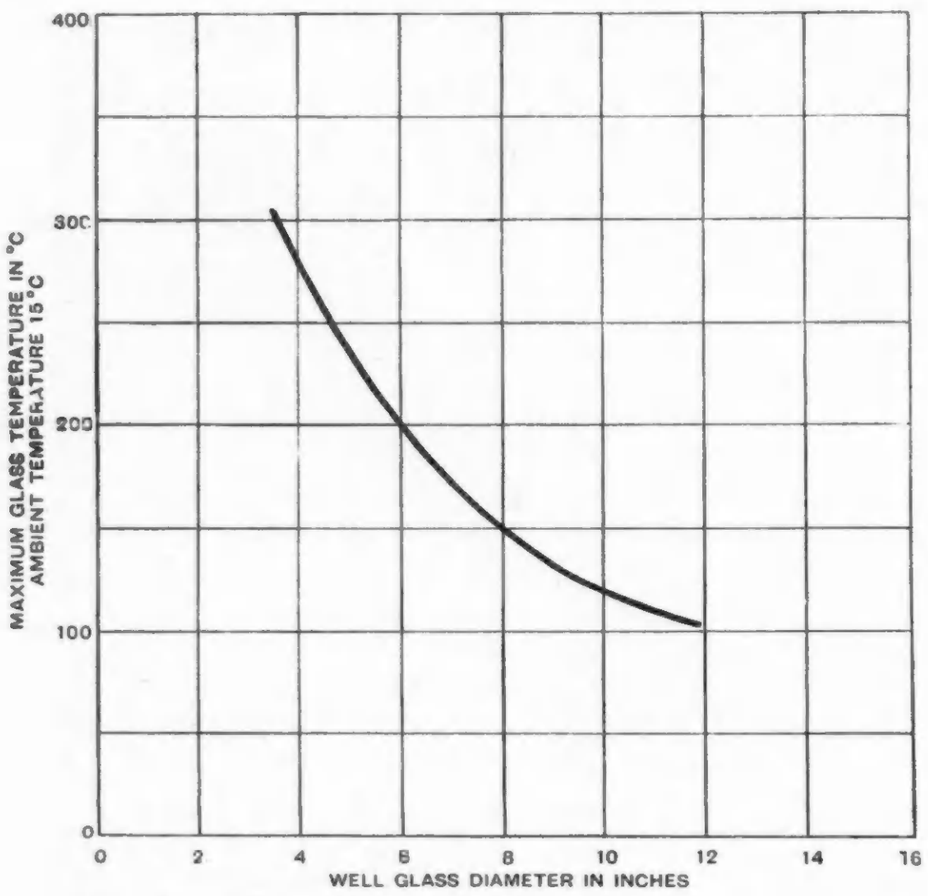


Fig. 9.—Curve connecting maximum well-glass temperature with diameter (400 watt "Osria" lamp).

is made of high efficiency opal glass) appears bright, to a degree determined by the size of the globe and naturally much less than that of the source itself. In such a case the distribution of intensity depends almost entirely on the shape of the globe, which

Fig. 10.—Method of attachment for well-glass.

here takes the form substantially of a truncated cone as shown in fig. 11. The intensity in any direction depends on the projected area of the globe in that direction, and the angle and dimensions of the truncated conical globe used in this fitting have been chosen to present the maximum area in a direction of about 60° to the vertical, and such area in other directions as to give a steady increase in intensity from a satisfactory value immediately downwards up to the maximum value at this angle, with a diminution at higher angles. Fig. 12 shews the polar curve of the unit which, it will be seen, has the essential characteristics of a good street lighting distribution as described above. The large area of low brightness eliminates the adverse effects of glare while providing a wide distribution, making this unit suitable for lighting large areas.

The reflecting type of unit on the other hand does not enclose the source, but produces the redirection of light by means of white vitreous enamelled metal cones designed to reflect light downwards where it is required and to cut off direct light from the source at high angles so that the brightness of the unit viewed from these directions is low. The unit (shewn in fig. 13) consists essentially of two cones of 70° semi-vertical angle, so placed relative to the source as to give minimum obstruction to direct light in the direction of desired maximum intensity (70° to the vertical) and a complete cut-off of direct light at 85° to the vertical. The position and size of the lower cone control the downward light, and the diameter

Fig. 11.—Symmetrical diffusing unit.

of the inner edge is particularly important in this respect. It must be large enough to allow a protective glass cylinder to be inserted round the lamp, but not unnecessarily large, or a valuable portion of the brightest part of the reflector will be lost. If an open cylinder of good heat resisting glass is used, the diameter of the hole need not exceed 4 inches for the glass to be capable of withstanding rain splash without fracture. By careful adjustment of the

several factors a distribution of the required type can be obtained. To achieve the same result with a single cone would demand much too large a fitting, while experiment has shown that to increase the number of cones above two introduces complications in construction and maintenance without any appreciable advantage.

Asymmetric Fittings

The asymmetric street lighting units required no less novel treatment. It has already been pointed out that the bare source itself had a wide spread distribution. In the asymmetric unit, however, it is desirable that the intensities in a vertical plane containing the street shall be made considerably higher than those of the bare lamp by redirecting the light radiated by the lamp above the horizontal, together with a proportion of that going on to the houses and sidewalks.

The original lantern designed for use with the "Osira" lamp was the "Watford," illustrated in fig. 14, which employs a refracting system for the production of the main beams and opal glass panels to provide the general lighting in the vicinity of the fitting. For the main redirection the prismatic refractor proved to be ideal. By using refracting panels in the lantern, light could be collected over an angle of 100°

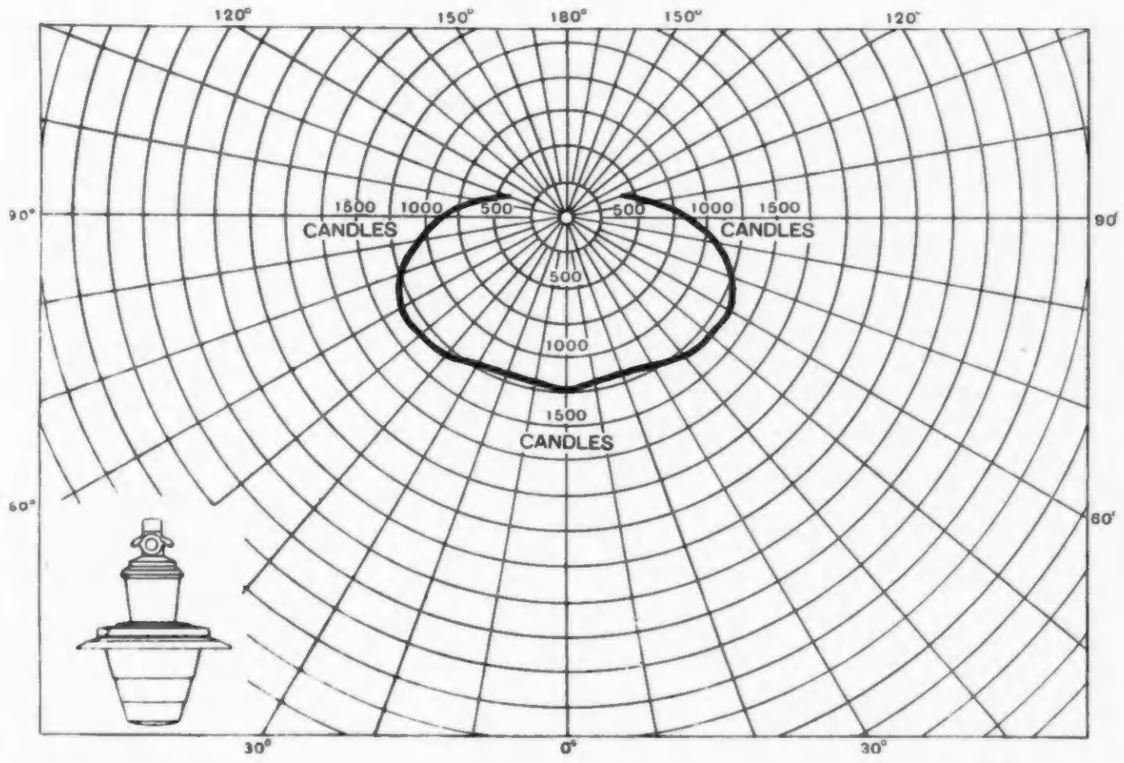


Fig. 12.—Polar curve showing light distribution in a vertical plane from symmetrical diffusing unit with 400 watt "Osira" lamp.

and redirected as required. To enhance the downward intensity of the source and to produce a light distribution which when combined with that from the refractors would produce a smooth polar curve, the lantern was fitted with a white enamelled inner top reflector and an opal glass bottom. The dimensions of the bottom were determined by the intensity required and this in turn controlled the plan size of the unit. The house side of the lantern was completed by an enamelled reflector whilst the street side was glazed with an opal glass bend to give general diffused light on the buildings and side walks. This construction enabled an efficient design of bracket for pole-mounting to be used.

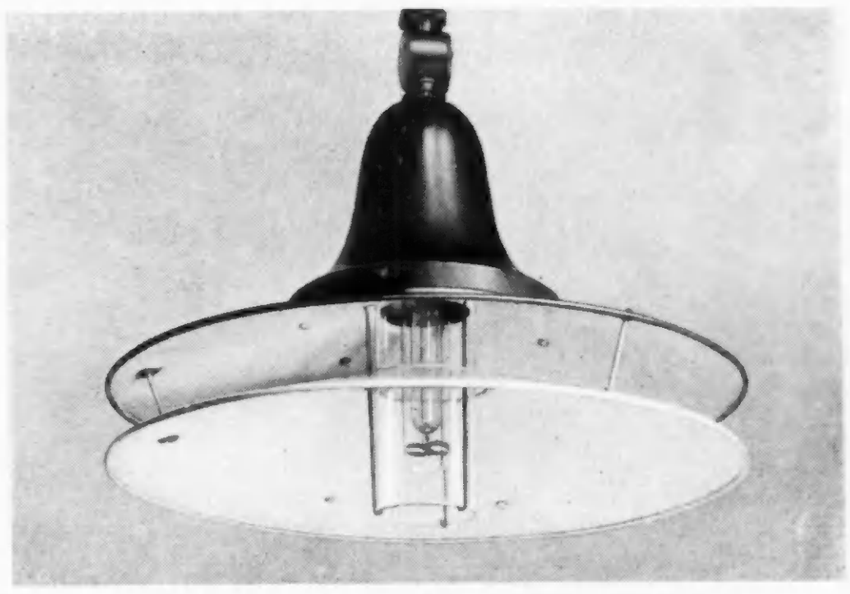


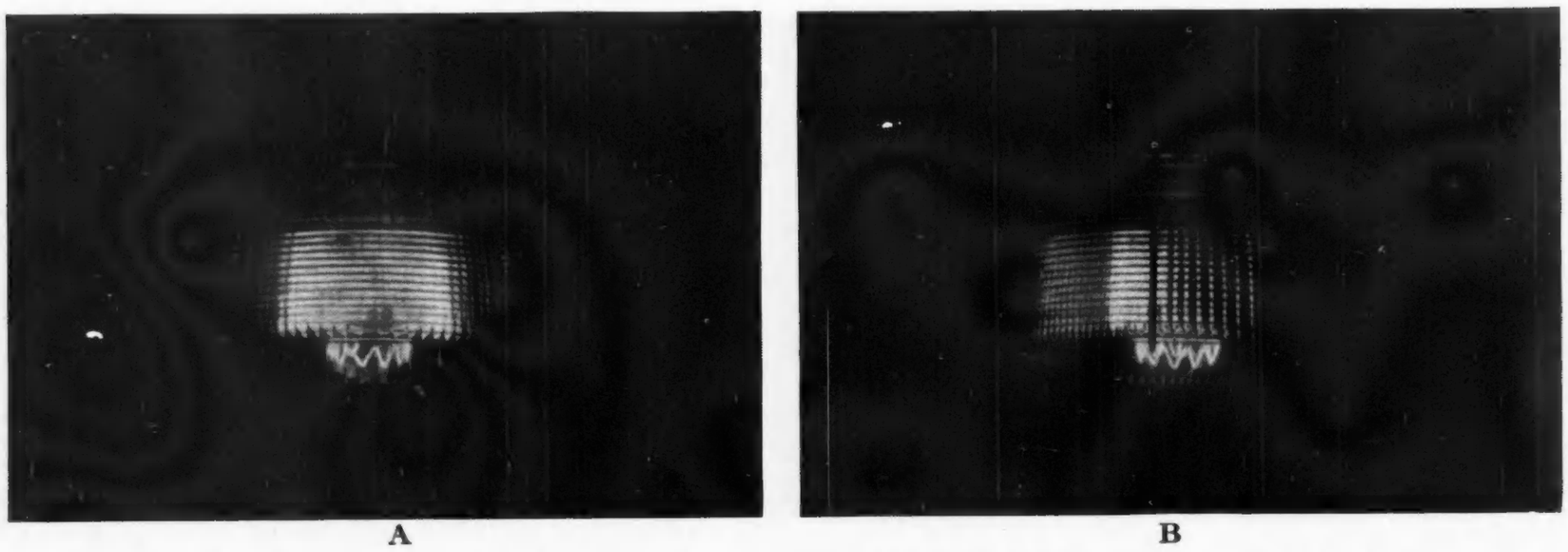
Fig. 13.—Rochdale louvre unit.

A novel feature was introduced into the refractor system. In older refractors for incandescent lamps, a simple image of the source was obtained magnified

Fig. 14.—Watford unit.

in one or more dimensions by means of prisms to produce the higher intensities. The typical appearance of such a refractor from two view-points is shown in fig. 15. The values of the intensity vary in proportion to the size of the image, while the brightness remains equal to that of the source itself except for transmission losses in passing through the glass. The new system renders the whole of the side of the lantern luminous as seen in fig. 16, and variations in intensity result mainly from variation

in the brightness rather than the size of this area. It will be clear that on account of the increased size of the effective source, for a given candle-power, the brightness will be much less than that required by the former method, and in fact the maximum brightness in the "Watford" lantern for a magnification of approximately twice the bare lamp intensity is not greater than 1/40th that of the source itself. This



A B

Fig. 15.—Appearance of bright areas in an asymmetric refractor of standard form. A—Direction of max. intensity; B—Direction of lower intensity.

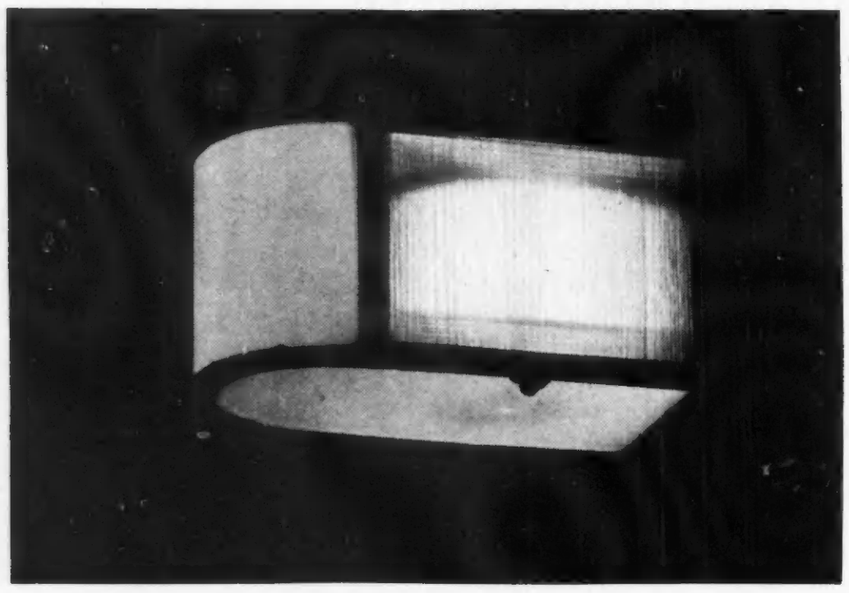


Fig. 16.—Watford lantern showing uniformity of brightness over surface of refractor plate—fluted glass panel.

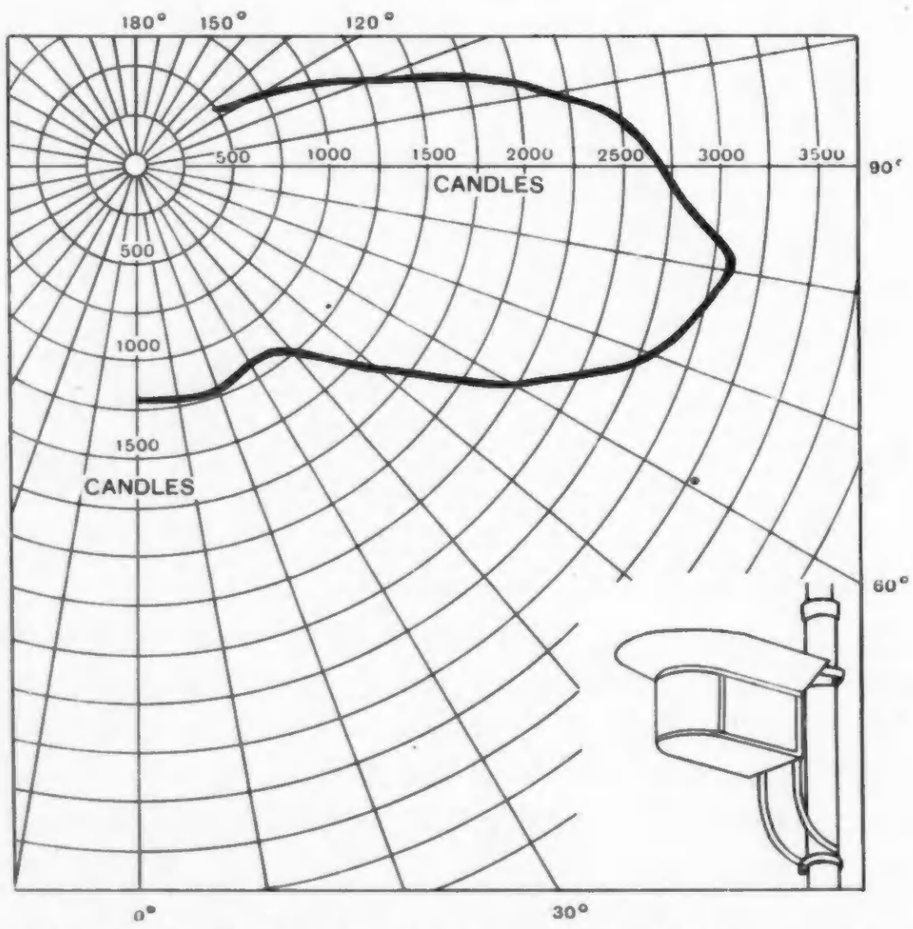


Fig. 17.—Polar curve showing light distribution in a vertical plane in direction of street, from the Watford lantern. 400 watt "Osira" lamp.

effect is obtained by first concentrating the light into a narrow angle beam by the prismatic refractor then diffusing it laterally to the extent desired by means of parallel flutes. In effect each flute produces a very narrow image of the source, the width of which varies with the direction of view. The eye cannot resolve all the fine images when viewed from a distance, and the result is an apparently uniform area whose brightness changes with direction of view. The prisms and flutes are vertical, parallel to the source. To have the whole of the side of the lantern bright when viewed from the road, while maintaining good proportions in the dimensions of the lantern, a row of horizontal prisms has been added to the top and bottom of the refracting plate. No other horizontal prisms are used so that full advantage can be taken of the natural wide spread distribution of the lamp itself. Some idea of the spread of the distribution can be gained from fig. 17. The polar curve which is for a vertical plane parallel to the street direction shows how high intensities are maintained at angles approaching the horizontal. It is the light emitted at these angles which, as shown by fig. 18 reproduced from Waldram's paper,* produce the large areas of high brightness in the street. This curve alone gives no information on the distribution of light round the unit, but the isocandle diagram in fig. 19 shows that high intensities are maintained over a wide angle. In this diagram the space around one side of the unit is shown as the projection of a hemisphere and the light distribution is shown by contour lines joining points of equal candle-power.

A similar type of unit is the "Lewisham" lantern, shown in fig. 20, which embodies the same refractor diffuser combination, but in another form. Its construction enables it to be suspended from a

* G.E.C. Journal VI. p.67, May, 1935.

bracket or span-wire, whereas the "Watford" must be mounted on the pole. The small "Tunbridge Wells" lantern (fig. 21) is the simplest form of this lantern embodying the same optical principles and is frequently used with the 250-watt as well as with the 400-watt lamp.

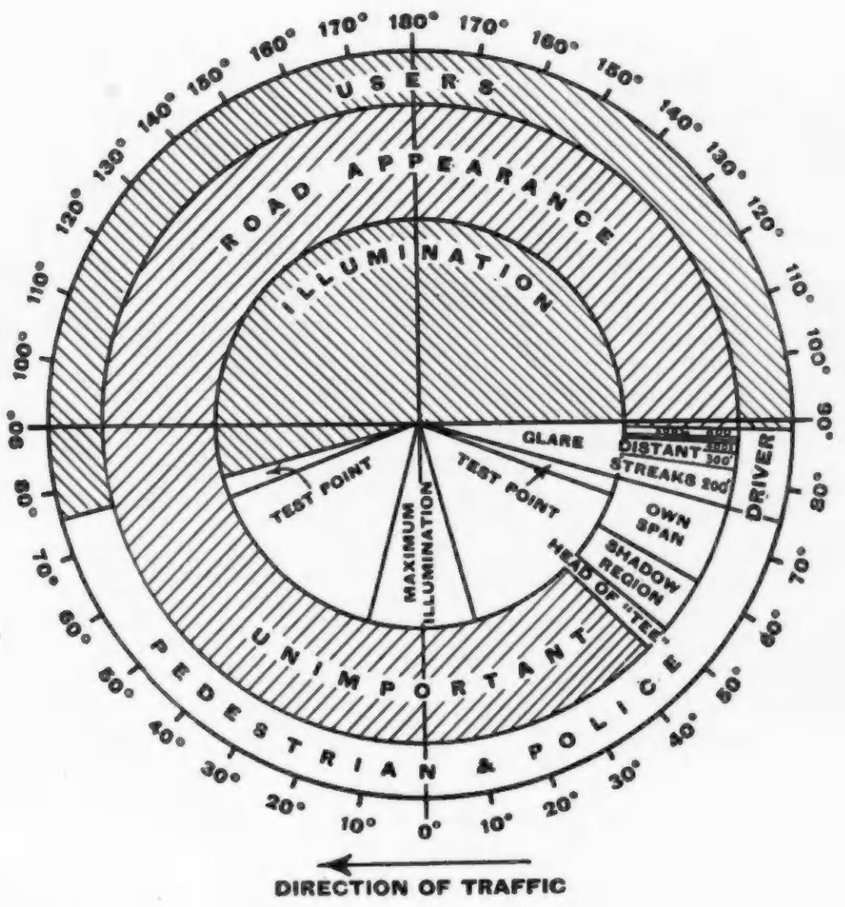


Fig. 18.—Analysis of the functions of light distribution in vertical plane.

Fig. 20.—Lewisham lantern.

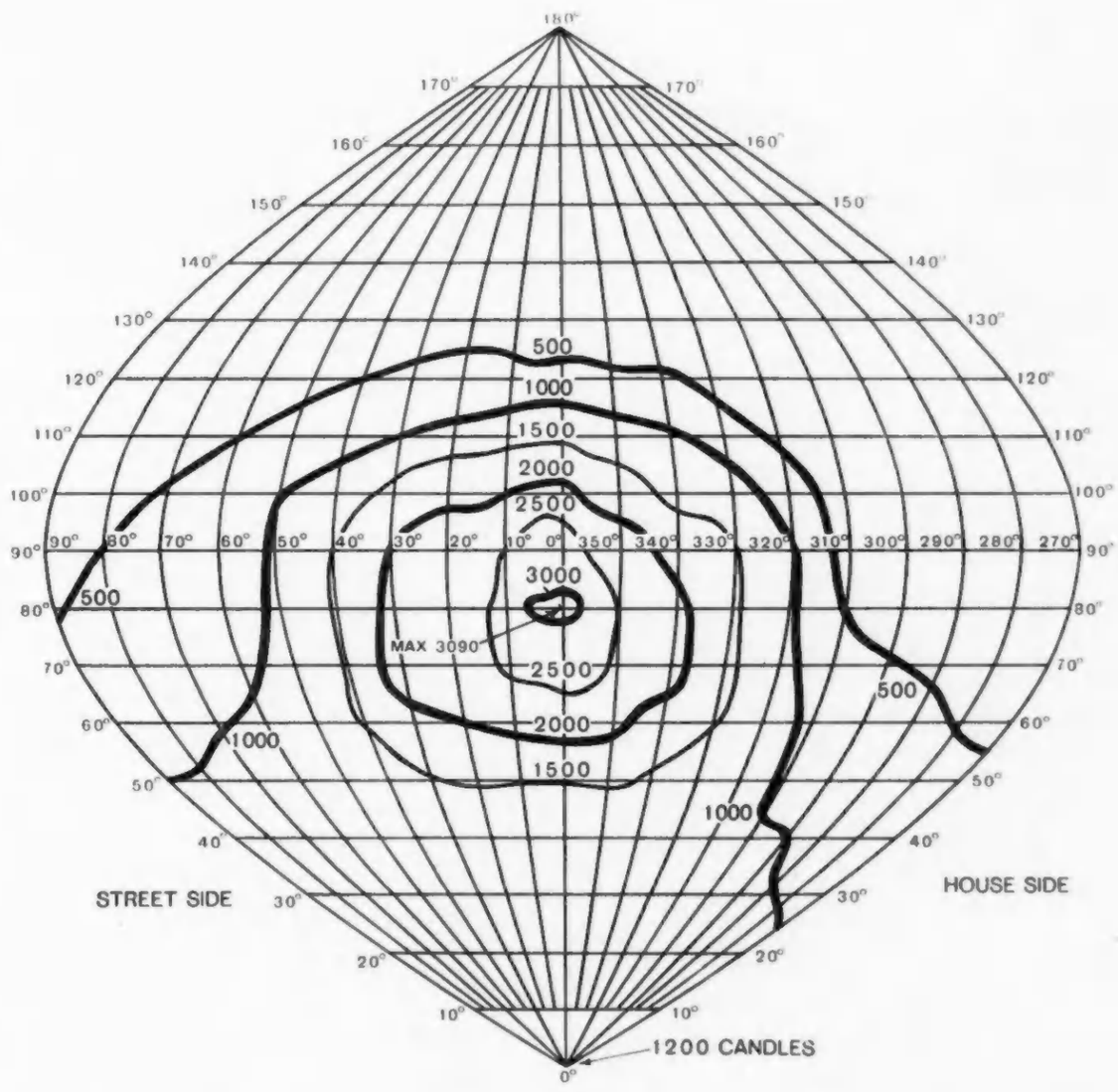


Fig. 19.—Isocandle diagram showing light distribution from Watford lantern with 400 watt "Osira" lamp.

One-Piece Asymmetric Refractor Unit.

A further development of this idea which appeared desirable, was the combination of the concentrating prisms and the diffusing flutes on the one piece of glassware. By making this circular, in addition, a simple spun housing could be used, and by choosing the size correctly a glass which could be applied at once to existing installations of "Wembley" filament lamp lanterns was produced. A lantern of this new form of refractor for use with 250-watt or 400-watt "Osira" lamps is shown in fig 22. In the one-piece circular form of glass, shown in detail in fig. 23, two main gangs of concentrating prisms A are placed inside and the diffusing flutes outside. The flutes are concave and very shallow, so that they do not collect dirt and can easily be cleaned by the wipe of a cloth. In place of the opal glass for diffusion, specially designed diffusing formations have been introduced. At the sides of the unit, round-topped corrugations B and C spread the light in all directions laterally, so that this portion of the glass appears bright from whatever direction it is seen. Although these corrugations are external, the light emerges almost entirely from the rounded top, where dirt does not tend to collect, and which is easily kept clean. The actions of the flutes and prisms are shewn in fig. 24. The first illustration shows how light from the lamp falling on the prisms is concentrated into parallel beams and subsequently spread the appropriate amount by the external flutes. In the second part of the figure are shown the ray paths in the special rounded top corrugations providing the wide angle diffusion. The bottom of the bowl is covered with an array of small cones of specially chosen angles, D in fig. 23, designed to give adequate downward illumination and a steady increase of intensity at increasing angles to the vertical, as shown in the distribution curve of the unit, fig. 25.

So, it will be seen, the equivalent of the complete optical system of the "Watford" lantern has been reproduced in one piece of pressed glass. This is as much of an achievement for the glass maker as for the designer—probably more. Each prism angle

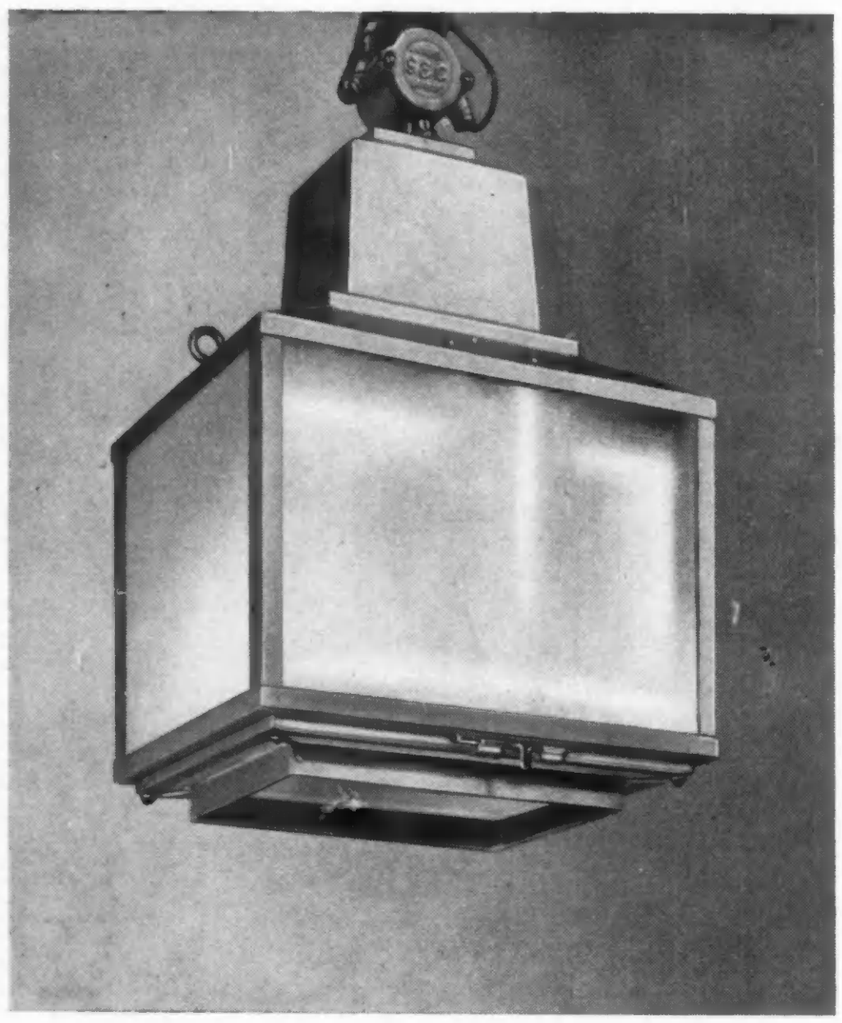


Fig. 21.—Tunbridge Wells lantern.

Fig. 22.—One-piece refractor-diffuser (Di-fuser) lantern.

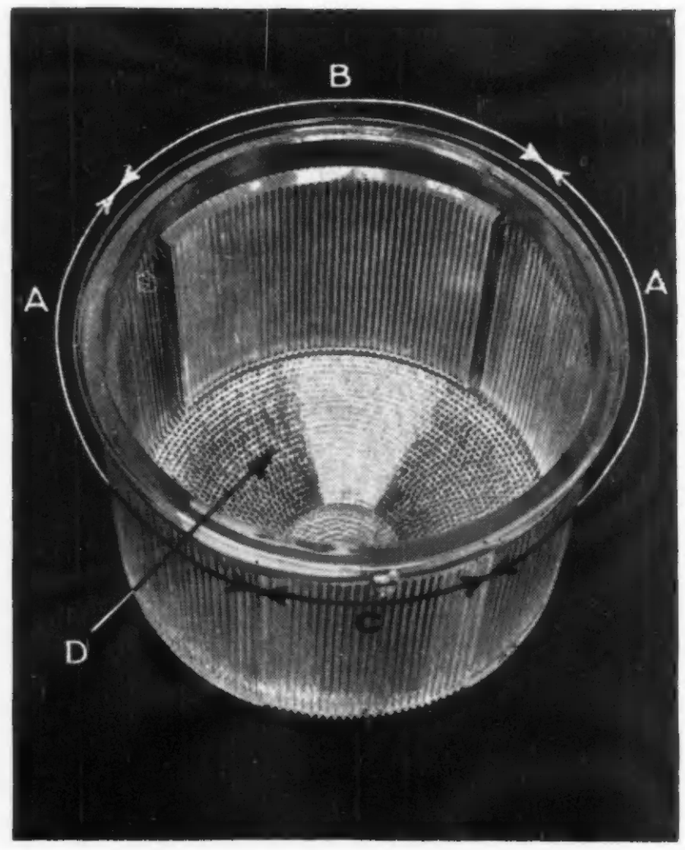


Fig. 23.—Details of refractor-diffuser.

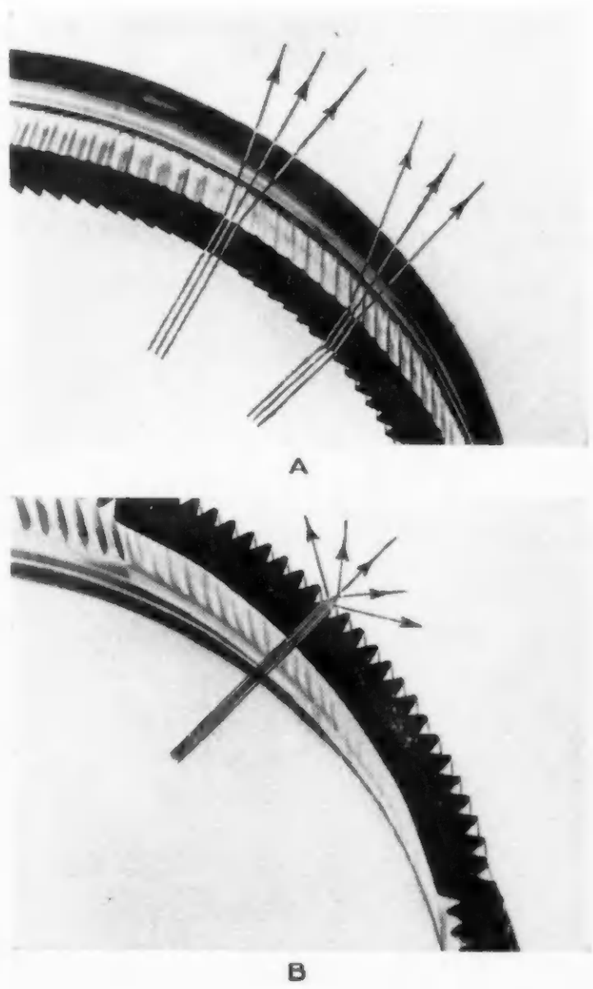


Fig. 24.—Ray paths in refractor diffuser.
A—Action of prisms and flutes.
B—Action of rounded top diffusing corrugations.

and flute radius as designed has been accurately reproduced in the finished heat-resisting pressing. A legend has been moulded on the base of the bowl to indicate the direction of the main beams, whilst a lug has been provided on the rim (visible at C in fig. 23) to ensure that the refractor is always fixed in its correct position in the lantern—practical points which ensure that careful design is not foiled by careless installation.

A description of special units for "Osira" lamps would not be complete without some reference to the results they can produce in service. They have been designed to take and redirect the light from the lamp so that in every application it is most effectively employed. In industrial lighting, illumination values can be increased above those given by the bare lamp by as many as five or six times; in street lighting the redirection is no less effective, but more important than the increase in illumination in this application is the improvement in visibility which can

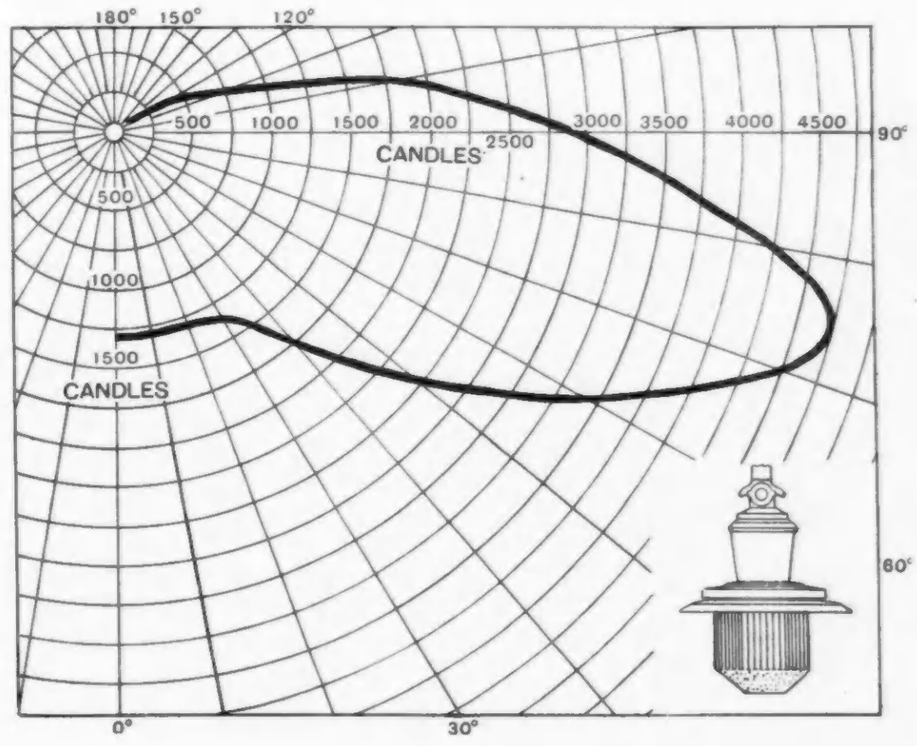


Fig. 25.—Polar curve showing light distribution from refractor-diffuser (Di-fractor) lantern in vertical plane in direction of street. 400 watt "Osira" lamp.

occur. One example is sufficient to show how the use of one of the new lanterns (actually that shewn in fig. 20) can produce an installation in which the visibility is almost if not quite as certain as in daylight. In fig. 26, every effort has been made to shew the results as they actually appear to an observer driving down the road. The pedestrian, clearly visible against the bright road surface, will be silhouetted in a similar way in every part of the winding road. Visibility is certain to the end of the installation nearly half a mile away—an adequate performance even for the rigorous demands of to-day.

Fig. 26.—An untouched reproduction of an installation of good street lighting using "Osira" lamps in correctly designed lanterns.

Voltage Regulation of A.C. Transmission and Distribution Systems.

PART I.—GENERAL CONSIDERATIONS.

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INTRODUCTION.

THE maintenance at a constant voltage of the electricity supply at consumers' terminals has always been a difficulty confronting the distribution engineer, but during the last few years it has become accentuated owing to the expansion of supply systems, the interlinking of power stations, the increase in demand for power, and the more critical attitude of consumers towards this aspect of their electrical supply.

The modern method of solving the problem is by the judicious application of regulating apparatus, the demand for which is rapidly increasing, due to the greater appreciation of its use by distribution engineers, advances in design and reduction in cost. Recent investigations show that nearly half the distribution systems in England have some regulating apparatus installed.

In this article some of the chief features of the regulation problem are discussed and the general scheme of transmission and distribution in Great Britain is outlined, the positions where regulating apparatus can be installed being shown. A second article will give the requirements of regulating apparatus illustrated in the schematic diagram, fig. 9.

GENERAL.

In accordance with the Electricity Supply Regulations 1934, the voltage of the consumers' supply must not vary more than plus or minus 6 per cent of the declared value. This variation is higher than is usually considered desirable on a good distribution system, but the maximum variation is required in rural areas where the problem is most difficult of solution.

In modern power station practice it is usual to keep the busbar voltage reasonably constant at the schedule value, while consumers at various parts of the system all require a constant voltage at their terminals irrespective of the variation of the load

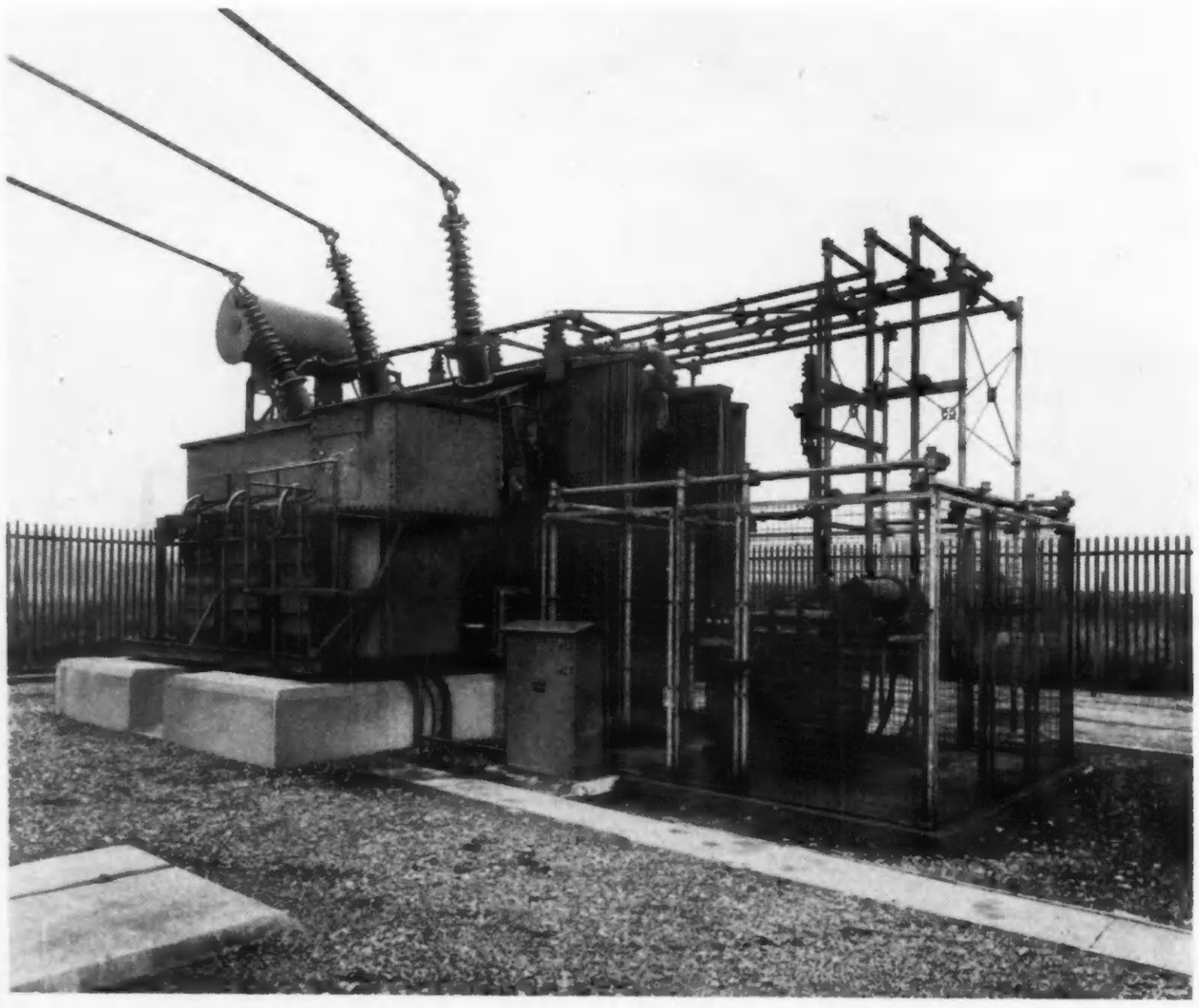


Fig. 1.—30,000 kVA transformer with tapping switch connected to the 132 kV winding. This switch is suitable for large transformers as installed at Stations S1, S3, S4, etc., shown in the diagram, fig. 9 on page 142.

voltage drop not only on their own local feeder, but on any feeder which ultimately connects them back to the power station.

An appreciation of a few of the fundamentals of system regulation, voltage regulating apparatus and transformer design is necessary before considering the transmission and distribution scheme.

TRANSFORMER REGULATION.

There are two main sources of voltage drop in a supply system; the transformer drop and the line drop. The transformer drop is due to the inherent reactance and resistance, the reactance becoming prominent on poor power factor loads.

Taking into account regulation alone, it is desirable that the reactance should be kept to a minimum, but the cost of transformers is increased if the reactance is reduced below a certain value, while the average efficiency decreases; further it is necessary to keep the reactance at a reasonable value in order to limit the short circuit current value in feeders, etc. This factor has grown the more important as the size of transmission systems and the power behind them has been increased.

The curves shown in fig. 2 give the normal transformer reactance and regulation for various sizes of transformers at full and three-quarter load, at both unity and .85 power factor.

The percentage regulation is given by the formula

$$IR.\cos\theta + IX.\sin\theta + \frac{(IX.\cos\theta - IR.\sin\theta)^2}{200}$$

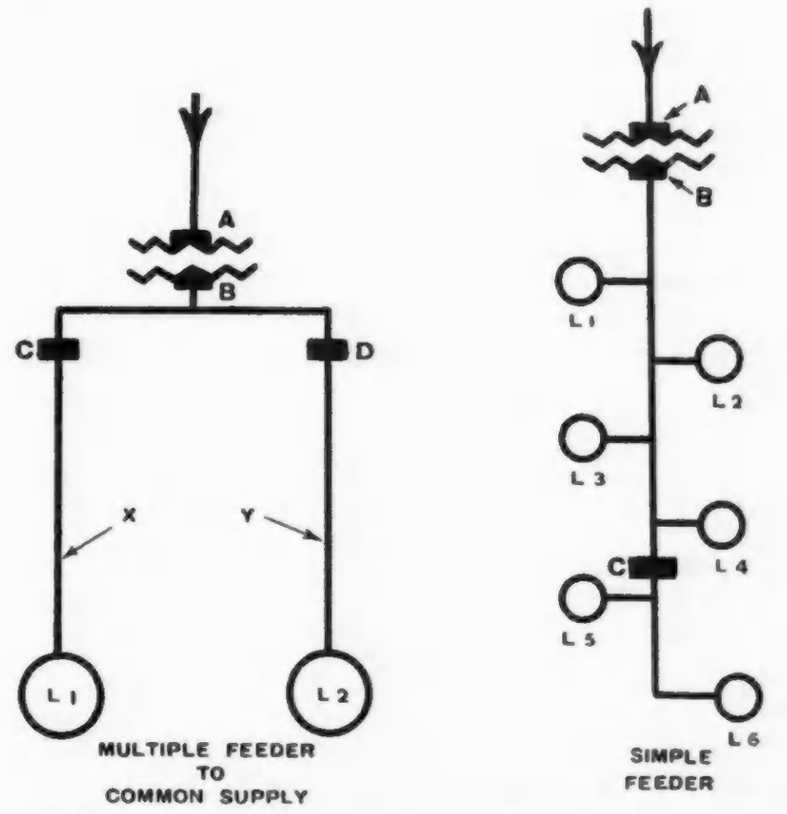
Where $IR.$ = % copper loss at load I.

IX = % reactance at load I.

θ = the phase angle of the load current.

common supply as shown in fig. 3, and secondly the simple feeder as shown in fig. 4.

Referring to fig. 3, L_1 and L_2 represent loads at the end of feeders X and Y respectively, these being connected to a distribution busbar fed from the secondary of a transformer. If the voltage drop at L_1 and L_2 at maximum load, is greater than desirable,



Figs. 3 (left) and 4 (right).—Diagrams showing principal circuit conditions affecting the position of regulating apparatus.

correction can be made by apparatus boosting the voltage according to the load voltage drop conditions. Should the voltage drop of both feeders be approximately the same and the time of loading similar, a boost can be given to the busbar voltage by means of a tap changer in the position A or B. If, on the other hand, the values of the voltage drops differ considerably or occur at different times, then the

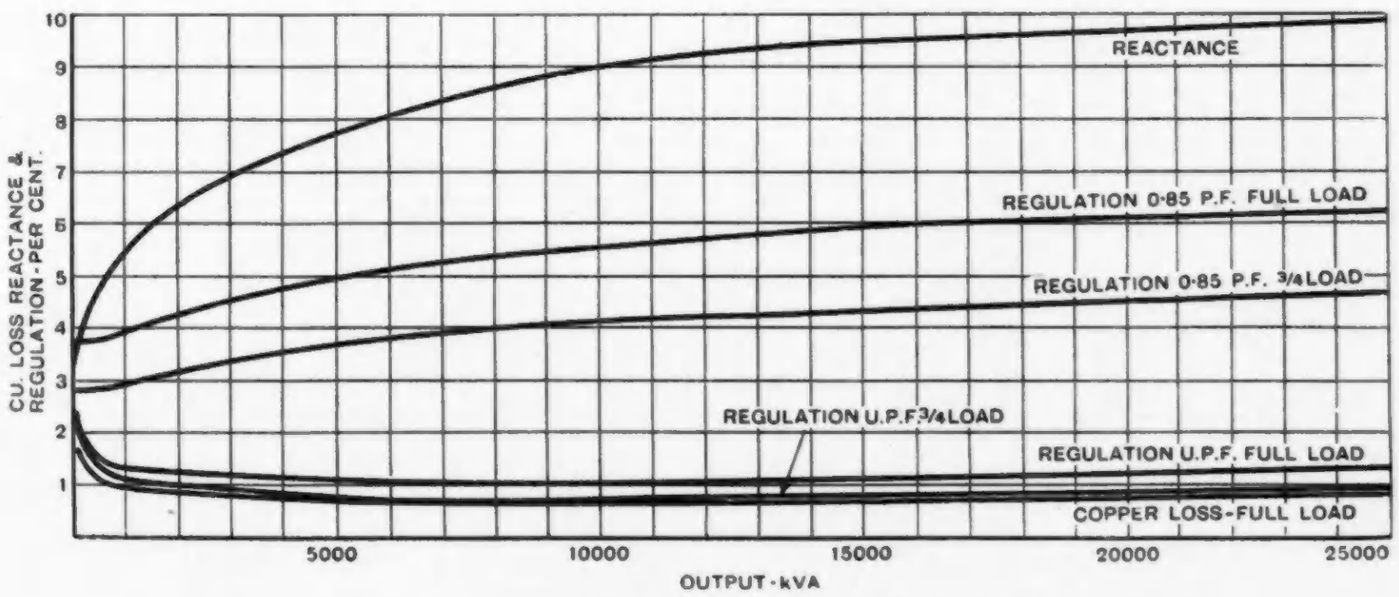


Fig. 2.—Curves showing percentage copper loss, reactance and regulation on transformers of various outputs.

CIRCUIT CONDITIONS.

There are two main circuit conditions that affect the position of regulating apparatus; first the voltage regulation of multiple feeders connected to a

two feeders must be regulated separately by boosters at the points C and D.

In the case of a long simple feeder (fig. 4) where an excessive voltage drop occurs and correction is

provided at A or B, it is necessary to make sure that on full boost the voltage of the load at the beginning of the feeder is not unduly high when the voltage is within the required limits at the end of the feeder. This may be corrected, if necessary, by reducing the amount of boost at the beginning of the feeder and introducing an additional boost towards the end of the feeder by means of a booster at some point C.

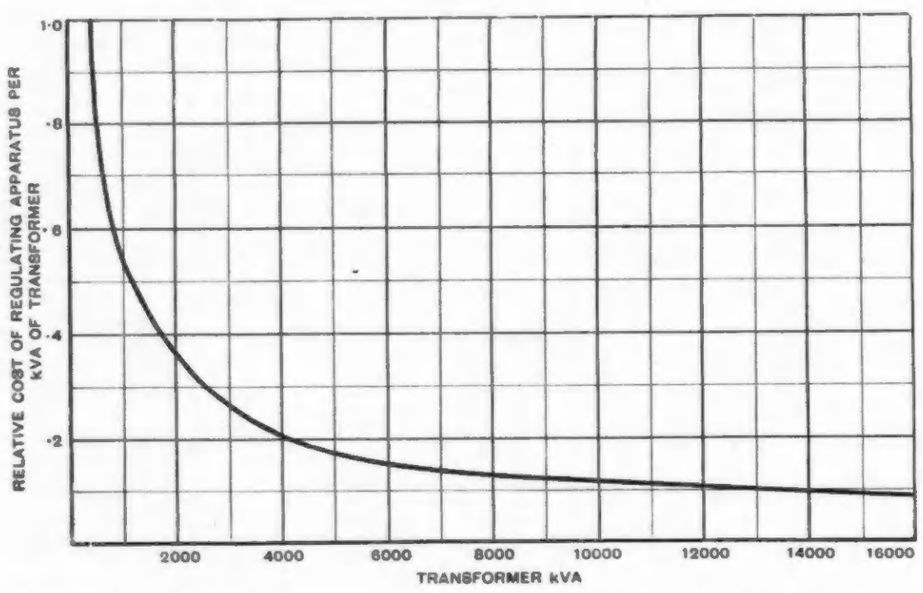


Fig. 5.—Relative cost per kVA of automatic on-load switches installed on transformers of various outputs.

Considering the simple feeder (fig. 4), without the booster at C, if a voltage regulator such as A at the beginning of the feeder is controlled to boost the voltage proportionally to the load, providing the voltage conditions are satisfactory along the feeder under the condition of maximum demand, the voltage condition will be satisfactory for any combination of loading or time of loading of the separate loads.

RELATIVE COST OF REGULATORS FOR VARYING SIZE OF TRANSFORMERS.

A curve of the relative cost against transformer kVA is given in fig. 5. It will be seen that the curve rises very steeply for tap changers on transformers under 2000 kVA, it is therefore commercially desirable that the voltage variation at any point of a system should be corrected as near as possible towards the generator. For example, considering the system shown in fig. 9, there would be considerable voltage variation with load due to the regulation of the 5000 kVA bulk supply transformer and its associated feeder at station S7. This could be corrected at the 5000 kVA transformer at a relative cost of .18 per kVA whereas if the voltage drop were to be corrected at the 500 kVA transformers further along the distribution system, the cost of correction would be about four times as much.

Although the remote control or automatic operation of voltage regulating transformer apparatus is obviously desirable and in many instances essential, it will be appreciated that the provision of the necessary equipment is expensive. The relative cost of the automatic gear and tap changer is given in fig. 6, from which it will be seen that the automatic gear bears a reasonable proportion to the cost of the tap changer for large bulk supply transformers, but may equal or exceed it for distribution transformers of 2000 kVA and below.

EFFECT OF REGULATORS ON THE DESIGN OF THE TRANSFORMER.

As the voltage regulation characteristics required of transformer tap changing gear affect the transformer design, it is essential that the exact requirements should always be given to the manufacturer.

In any typical installation the following regulation characteristics may be required :—

(*a*) A constant secondary voltage load characteristic with a varying primary voltage.

(*b*) A rising secondary voltage-load characteristic with a constant applied primary voltage.

(*c*) A rising secondary voltage-load characteristic with a varying primary voltage.

A variation from normal of the applied voltage to a transformer without voltage regulating apparatus will be reflected in the flux density and secondary voltage ; hence, an increase above normal voltage

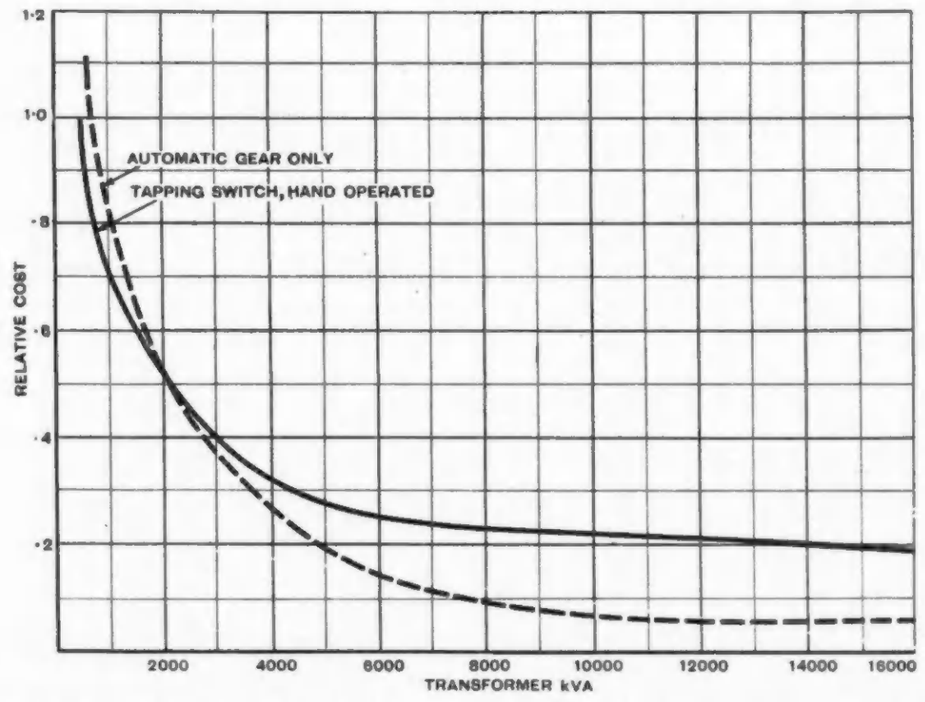


Fig. 6.—Relative cost of the tapping switch and automatic gear for complete automatic on-load tap changing equipments at various transformer outputs.

will give a corresponding increase in flux density, higher iron loss and harmonics, and greater noise. Alternatively, if the voltage is reduced below normal for a given kVA loading, the winding current and copper loss will be increased.

If a winding of a transformer is tapped for voltage regulation apparatus, the technical characteristics of the transformer will vary depending on whether the tap changer is connected to the primary or secondary winding, and also on the alternative regulation characteristics (*a*), (*b*), (*c*), given above.

The following table shows how the characteristics alter.

It will be seen that alteration takes place to the magnetic and/or electric loading, the magnitude of the alteration being proportional to the voltage variation ; it is therefore necessary during the design

of the transformer, to make any necessary correction or allowance in the iron or copper loading.

Table 1 shows that a tap changer connected to the primary winding to correct for primary supply voltage variation will only alter the primary current, whereas if connected to the secondary winding two characteristics will alter.

Again if the tap changer is used for varying the secondary voltage with a constant primary supply, then it will only alter the secondary current characteristics if connected to the secondary winding, whereas if connected to the primary windings two characteristics will vary.

In a similar manner, the requirement of a rising voltage/load characteristic with primary voltage variation will give varying transformer characteristics proportional to the sum of the variations of the separate voltage variation requirements.

From the foregoing, a general statement can be made that, viewed from a technical aspect, the tap changer should be connected to the primary winding if correction is required for a varying primary supply voltage, and to the secondary side when a rising voltage/load characteristic is desired, with constant primary supply voltage. Further, in the third case of a rising voltage/load characteristic with varying primary supply, all the characteristics will be affected, whichever winding is connected to the tap changer, and the final decision will depend on the magnitude of the separate variations.

These conclusions may be modified by the

TABLE 1.

Transformer Characteristic.	Constant Secondary Voltage with Varying Primary Voltage.				To Vary Secondary Voltage with Constant Applied Primary Voltage.			
	SWITCH ON PRIMARY.		SWITCH ON SECONDARY.		SWITCH ON PRIMARY.		SWITCH ON SECONDARY.	
	Volts above normal.	Volts below normal.	Volts above normal.	Volts below normal.	Volts above normal.	Volts below normal.	Volts above normal.	Volts below normal.
Flux density, Harmonics, Iron loss	Constant	Constant	Increases	Decreases	Increases	Decreases	Constant	Constant
Primary wdg. current	Decreases	Increases	Decreases	Increases	Constant	Constant	Constant	Constant
Secondary wdg. current ..	Constant	Constant	Constant	Constant	Decreases	Increases	Decreases	Increases

The above table neglects variation in characteristics due to the regulation of the transformer itself.

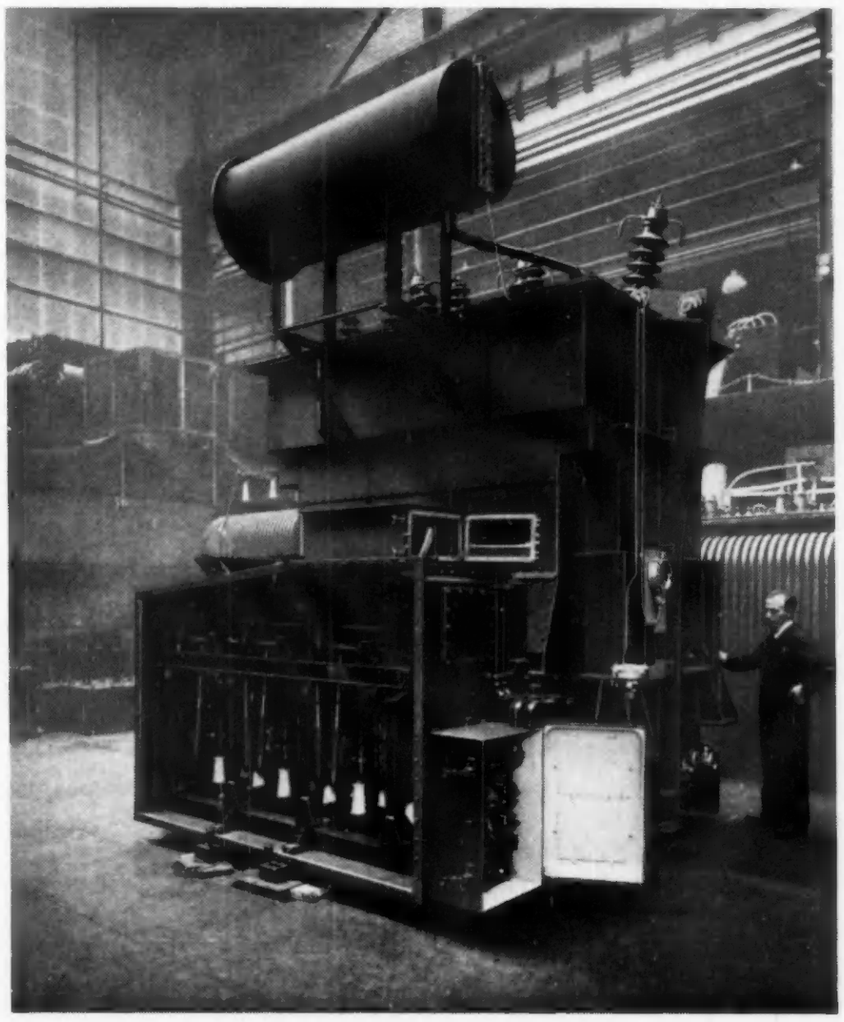


Fig. 7.—10,000 kVA Transformer with tapping switch as installed at stations S2, etc. in fig. 9, the switch being suitable for connecting to either the 132 kV or 33 kV winding.

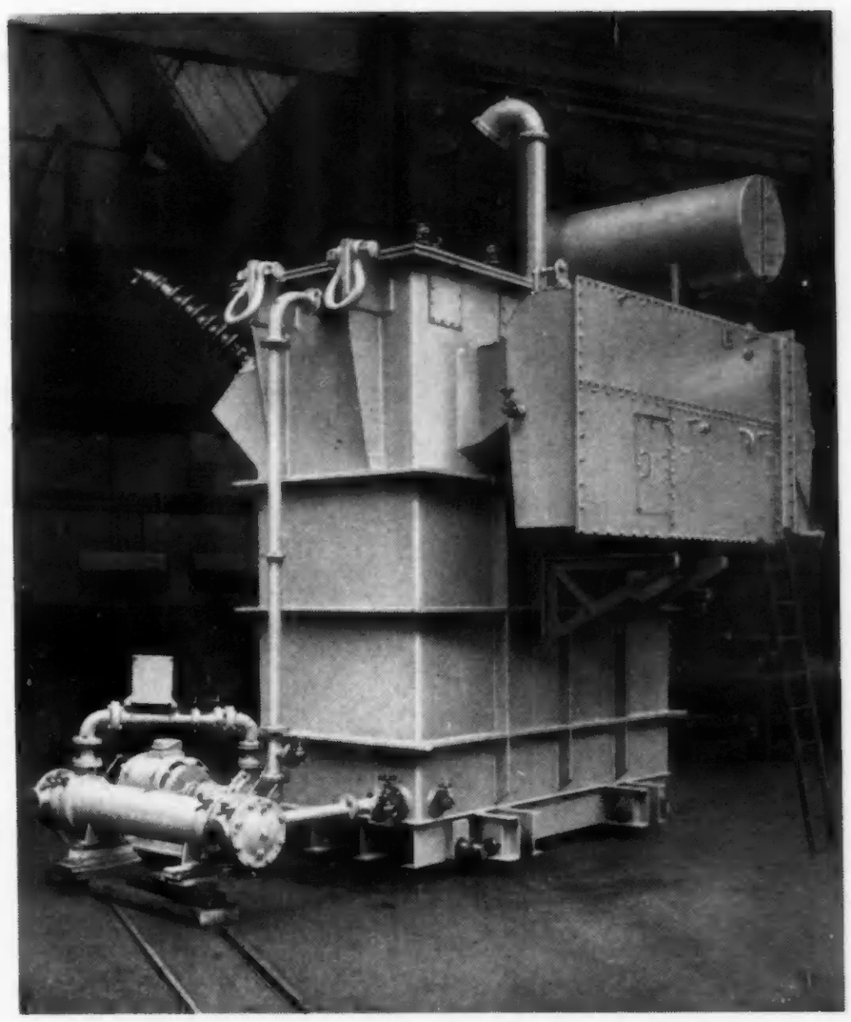


Fig. 8.—7,500 kVA Transformer, 66/6.6 kV, with a tapping switch suitable for connecting to windings up to and including 11 kV as shown at station S7 in fig. 9.

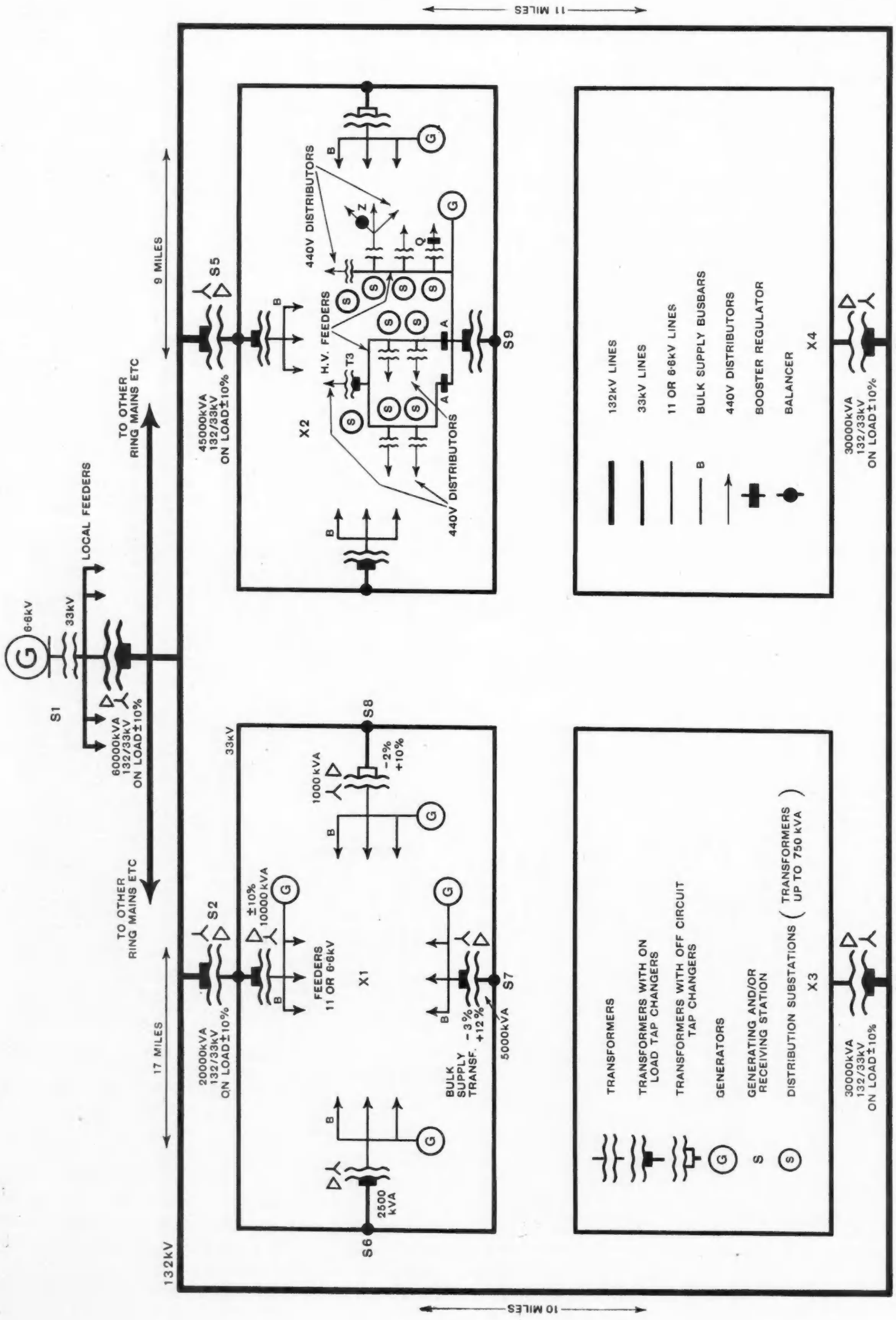


Fig. 9.—Schematic transmission and distribution diagram showing positions at which regulating apparatus can be installed.

question of difference in cost of switches of equal rating but different voltage, and it may be more economical to use a switch connected to the theoretically incorrect winding, and decrease the magnetic and/or electric loading to compensate for the variations which will occur in the transformer characteristics.

Bearing the foregoing fundamental principles in

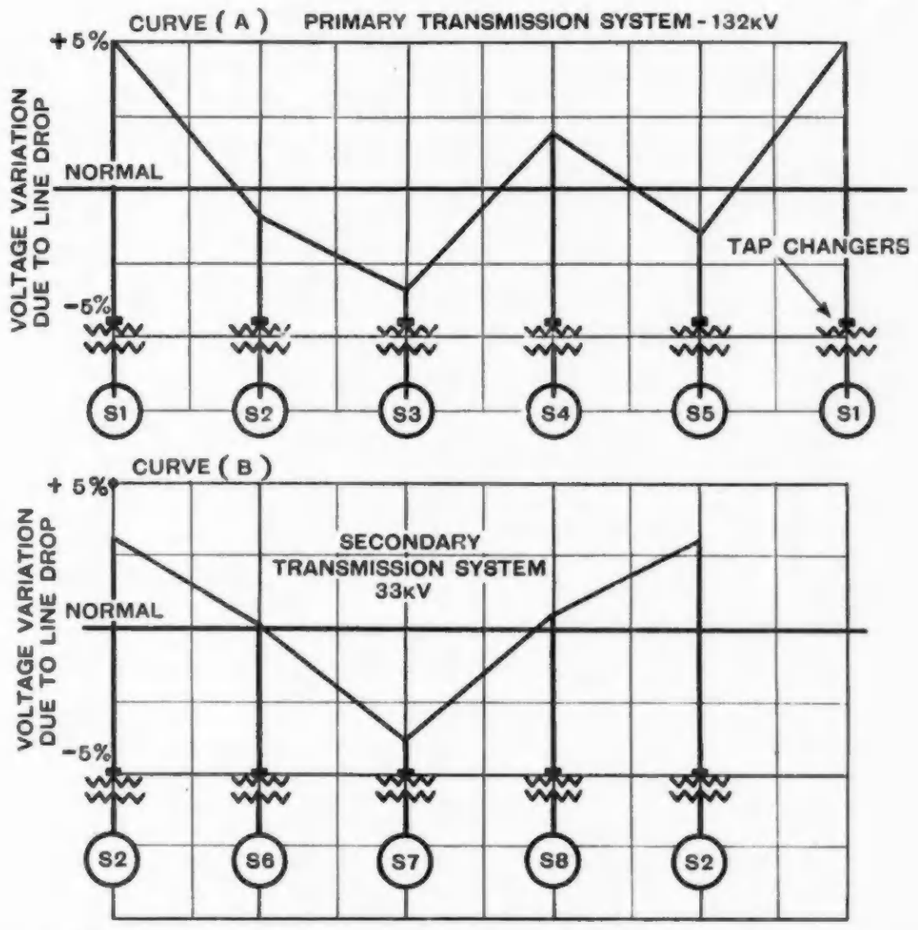


Fig. 10.—Curves A and B show the regulation of the primary and secondary transmission scheme given in fig. 9.

mind, the transmission and distribution scheme shown in fig. 9 may now be considered from the aspect of voltage regulation and correction by means of voltage regulating apparatus.

THE TRANSMISSION SYSTEM.

The British grid system consists of a primary network operating at a nominal voltage of 132 kV and secondary networks operating at 66 or 33 kV; these networks co-ordinate the operations of power stations and supply bulk power to the authorised undertakings who distribute the power to the consumers.

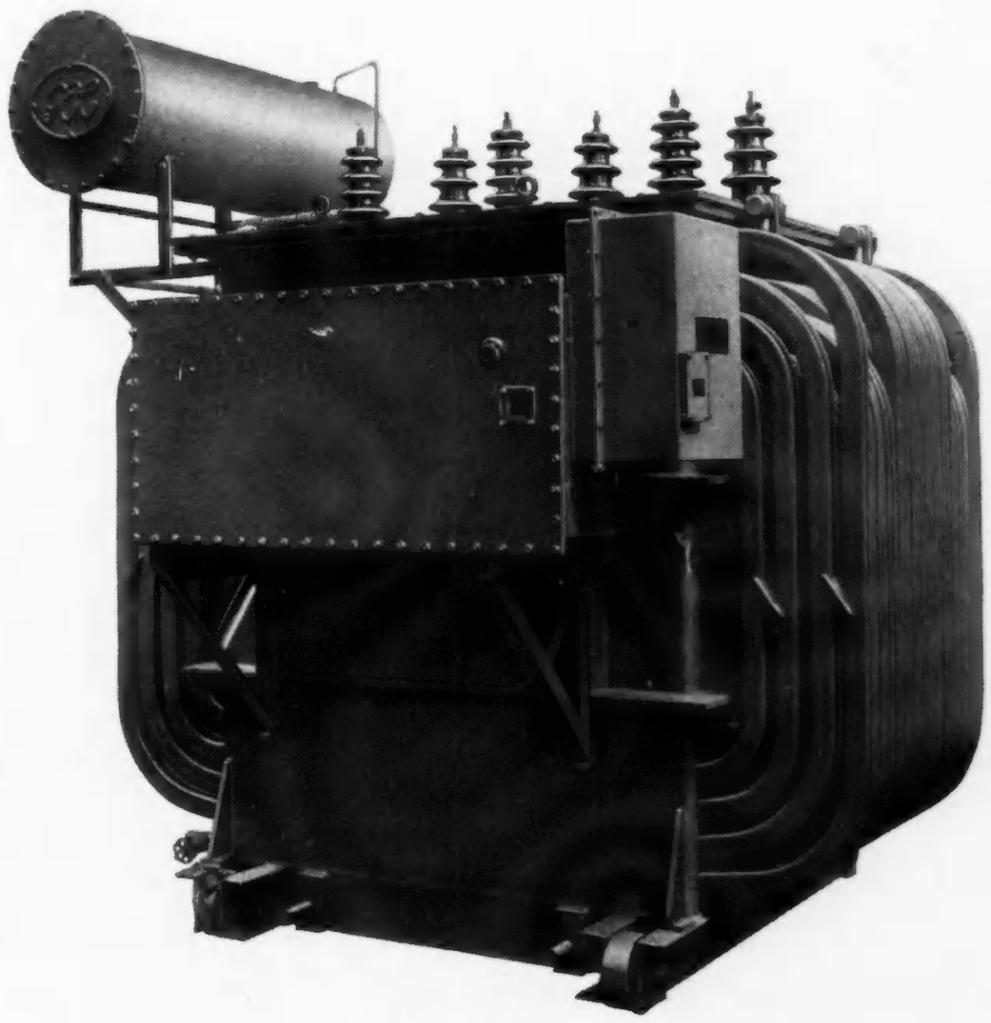
A schematic diagram of part of the primary transmission system is shown in fig. 9, covering an area of, say, 300 sq. miles, and four 33 kV secondary transmission systems X1 to X4, each covering a quarter of this area. The system may be regarded simply as national busbars to which the supply systems of towns are connected, each town either giving or taking power.

The voltage along the systems rises and falls above the nominal value depending on the load carried, representative voltage curves being given in fig. 10. The voltage curve of the primary system shows stations S1 and S4 supplying power to the 132 kV system, while stations S2, S3, and S5 are shown receiving power.

The secondary transmission being essentially for receiving power from the 132 kV system, stations S6, S7 and S8 are shown receiving. Curve "A," shows that the maximum regulation likely to be experienced on the primary system will be within 10 per cent, *i.e.* the voltage will be kept within 5 per cent of normal; this is the normal case although in some districts it is higher.

The Central Electricity Board usually supply bulk power to the authorised distributors on the lower tension side of the bulk supply transformers, and the variation of voltage at that point is necessarily governed by the statutory limits of plus and minus 6 per cent, but it is highly desirable that the voltage at this point should be kept approximately constant or, better still, given a slightly rising voltage/load characteristic. This is done to save the cost of correcting the regulation at this point by relatively more expensive apparatus on transformer units of smaller power situated towards the consumers end of the distribution system. In order to obtain the desired characteristic at the bulk supply busbars, the transmission and transformer system must be flexible.

To appreciate the flexibility available, an example of the regulation at the bulk supply busbars at Station S7 may be considered, assuming that a rising voltage/load characteristic of 3 per cent is required at a load corresponding to 75 per cent of the trans-



3,500 kVA Booster for connecting in a feeder supplied by a transformer without a tap changer.

former capacity with a power factor of .85. At the given load a boost of 3 per cent is required on the 11 kV side; to this must be added the regulation of the transformer, say $3\frac{1}{2}$ per cent, (fig. 2), giving a necessary boost of $6\frac{1}{2}$ per cent. According to the voltage characteristic of the secondary transmission system, fig. 10, the voltage of the supply may be 4 per cent low, and hence a range on the tap changer

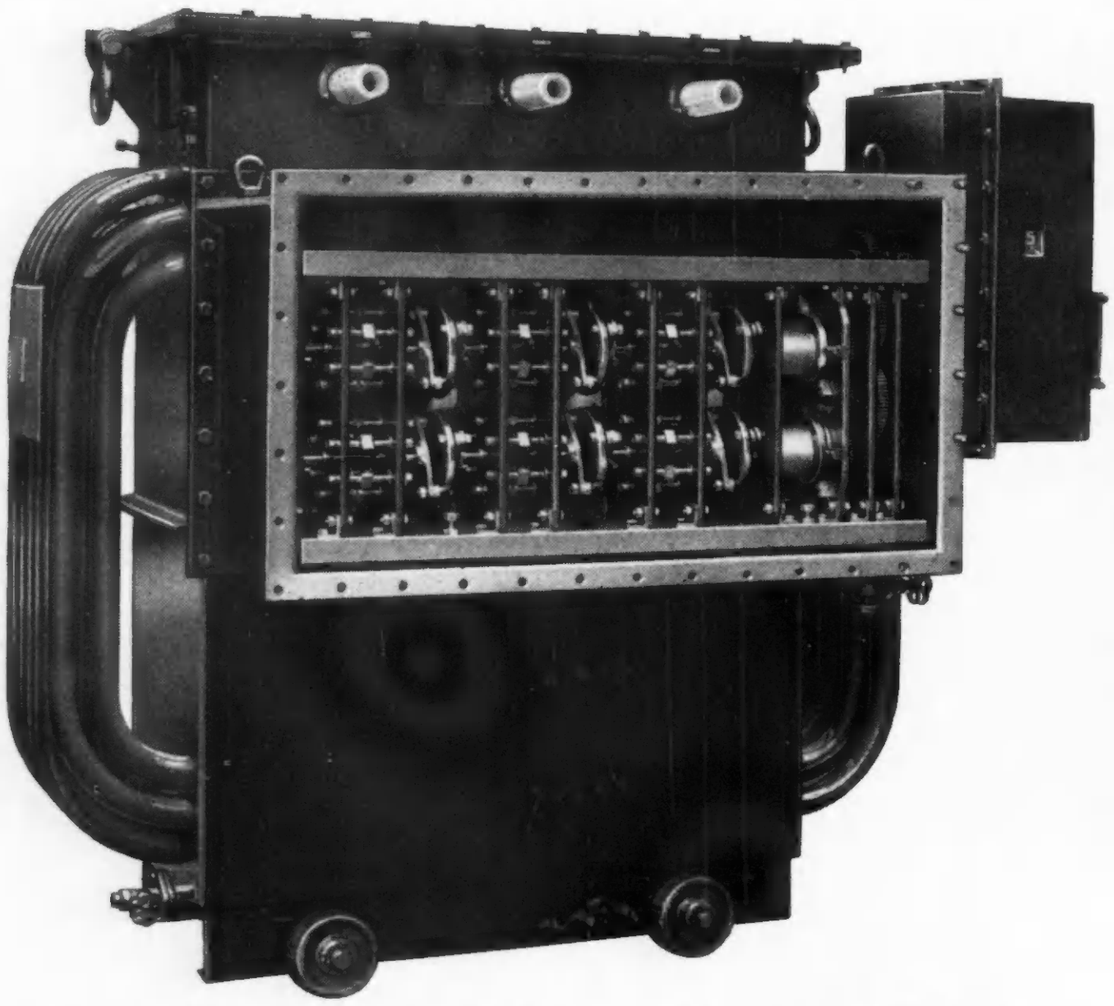


Fig. 12.—300 kVA Transformer with tapping switch suitable for connecting to the higher voltage side of transformers T3 in sub-stations (S), fig. 9.

is required to boost the voltage by $10\frac{1}{2}$ per cent.

As the greater part of this voltage adjustment is to boost the lower voltage and not to correct for primary supply voltage variation, in order to keep the flux density in the transformer as constant as possible, the tapping switch should be on the lower voltage winding, not only because this position is the theoretically correct one, but also because a switch on the lower voltage side of a transformer of this capacity would probably be cheaper.

In order to keep the voltage on the high tension side of the bulk supply transformer to within the minus 4 per cent assumed, the 33 kV busbar voltage at the intermediary Station S2, which steps down from 132 to 33 kV, must be raised 3 per cent above normal (see fig. 10b). It is now necessary to consider the 132 kV system to see by what means the voltage on the secondary of the transformer at S2 can be raised to 3 per cent above normal.

As shown in curve "A," fig. 10, the voltage along the primary system rises and falls depending on the load conditions. Theoretically each station supplying current to the system should do so at the normal power factor of the distribution system, which is about .85. The power supplied by a station is controlled solely by the setting of the steam governor, but at a given power factor of supply, the voltage of the transmission system must be raised at that point to allow for the voltage drop in the transmission line, due to the current flowing.

Neglecting the voltage drop in the transformers, the tap changers at Stations S1 to S5, will be adjusted to give a transformation ratio such that the higher tension voltage will correspond to the voltage regulation curve of the system at that point as required to give the correct flow of power.

In order to increase the voltage by 3 per cent on the secondary transmission system as required in the example under consideration, the tap changer on the 132 kV transformer at S2 must be operated so that the transformer ratio is reduced below the requirement necessitated by the power flow between stations. This operation will increase the voltage throughout the secondary transmission system and increase the flux density of the transformer proportionally to the 3 per cent boost required; it is essential that the transformer designer should take this into

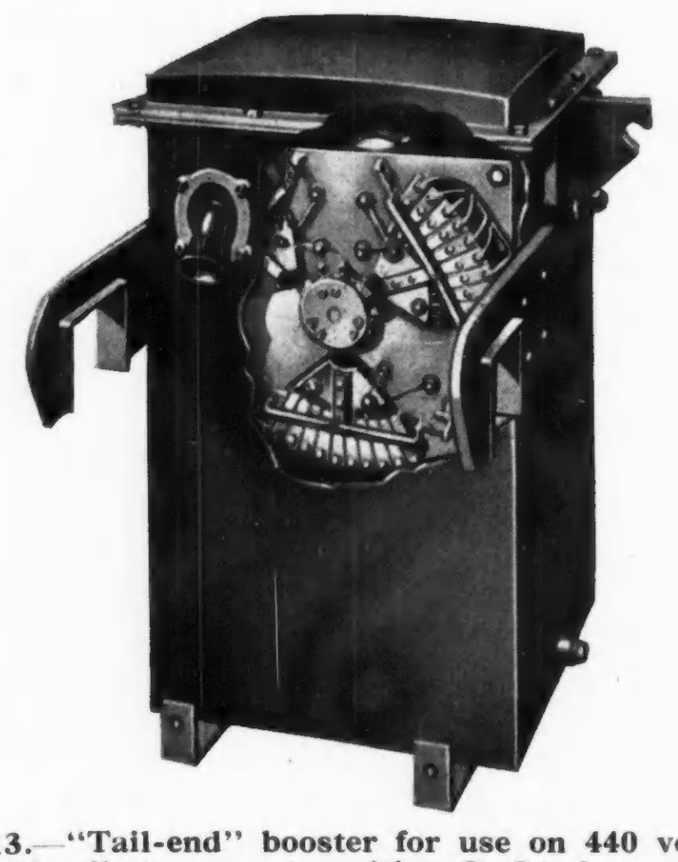


Fig. 13.—"Tail-end" booster for use on 440 volt distributors as at position Q, fig. 9.

consideration otherwise the flux density may rise to too high a value, resulting in the introduction of excessive noise, fifth harmonics, iron losses, etc.

It is interesting to note that the shape of the voltage curve of the primary transmission system, curve "A," fig. 10, can be retained, but raised above normal by raising the voltage ratio of the tap changers at all stations. By this means the normal voltage of the system is raised, but the power flow between stations, the secondary transmission voltage, and the

flux density of the transformers all remain unaltered.

In a similar manner the Grid voltage may be reduced if required.

Fig. 14.—Balancer for improving regulation of unbalanced 3 phase, 4 wire, 440 volt distributors installed in positions such as Z, fig. 9.

THE DISTRIBUTION SYSTEM.

High Tension Feeders.

The distribution engineer has now to convey the energy from the bulk supply busbars B, to the consumers, maintaining the voltage of supply at the consumer's terminals within the statutory limits of plus and minus 6 per cent.

It will be noted that distribution is usually carried out at 11 kV or 6.6 kV; these voltages are usual in Great Britain because of the frequent tapping of supply feeders necessitated by the ribbon system of housing development. In countries with infrequent villages, etc., 33 kV distribution is commonly used, as although the cost of tapping the feeder is much greater it becomes a practical proposition and the voltage regulation is thereby improved.

In the scheme illustrated in fig. 9, station S9, ring mains, radial or parallel feeders emanate from the bulk supply transformer busbars. If good regulation is not obtained at this point boosting regulators may be installed at point A to rectify the regulation on those feeders where trouble is experienced.

These high voltage feeders usually link into distribution sub-stations S in which are installed transformers the capacities of which range from 50 to 500 kVA. These step down the voltage to 440/230 for four wire distribution networks. Voltage regulators T3, are sometimes necessary on such transformers owing to the excessive voltage variation of the feeders, especially in the case of extensive ring mains feeding sparsely populated areas. Up to the present not a great number of this type of regulator have been installed, as the cost of the regulators has been considered prohibitive, but owing to the rapid advance which is being made in regulator design coupled with a reduction in cost, the future demand may be considerable.

In certain cases, commercial considerations may not warrant an extension to an H.T. feeder and the expedient may be resorted to, of installing a transformer, T3, with regulating apparatus, boosting the secondary voltage, and running a long low voltage feeder which normally would have too bad a regulation, but is capable of being corrected by the regulator.

LOW VOLTAGE NETWORKS.

Low voltage distributors can rarely be loaded to their full thermal rating on account of the voltage drop, and a good case can thus frequently be made for the installation of regulating gear. When assessing the question of economics, the loss of revenue due to metering under voltage should also be taken into account.

In certain cases it is necessary to run a long low voltage distributor, or extend one already laid down to such an extent that bad regulation becomes inevitable, even though a regulator is installed at such a position as T3 (fig. 9).

In this case correction can be made by means of an automatic tail-end booster, Q.

Bad voltage regulation on a four wire distribution system may be brought about by a general or localised unbalancing of the 4-wire system, such as might be produced by cooker loads, the out-of-balance current in the fourth wire causing the poor voltage regulation.

Fig. 15.—25 kVA Static booster for use at position Q, fig. 9, on low voltage distributors or on small distribution transformers as in sub-station S at position T3.

This condition may be overcome to a certain extent by the use of interconnected star balancers, "Z," which reduce the voltage drop in both the fourth wire and supply transformer.

(To be continued).

Turbo-Blowers and Turbo-Compressors.

PART I.

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TURBO-BLOWERS, turbo-compressors, turbo-exhausters, turbo-boosters, fans and turbo-superchargers are based on the same principle of operation; the different names indicate broadly rather the pressure increase effected or the particular application.

These machines can be divided, according to the direction of the gas flow in the impellers, into two classes, radial and axial. The radial or centrifugal type was originated by Prof. Rateau, while the axial type was introduced by C. A. Parsons. This latter type was, however, almost abandoned, to reappear recently in an improved form. Fraser & Chalmers Engineering Works built the first Rateau turbo-blower in this country in 1908; since then other firms have taken up the manufacture of this type of machine.

While this article will deal with the radial type of turbo-blower and turbo-compressor, certain parts of it will be applicable to any type of the turbo machines mentioned.

PRINCIPLE OF OPERATION.

The principle of operation of turbo blowers and turbo compressors is as follows: (*a*) Mechanical energy from an outside source (motor) is transmitted by the shaft and impeller to the gas in the impeller, the gas acquiring a certain amount of kinetic energy; (*b*) This kinetic energy is converted wholly or partially into heat energy in the impeller and the following diffuser.

(*a*) KINETIC ENERGY IMPARTED TO GAS.

Referring to fig. 1, which shows one stage in diagrammatic form, the power input in the impeller for 1 lb. of gas flowing through the impeller per second is represented by the well known formula:

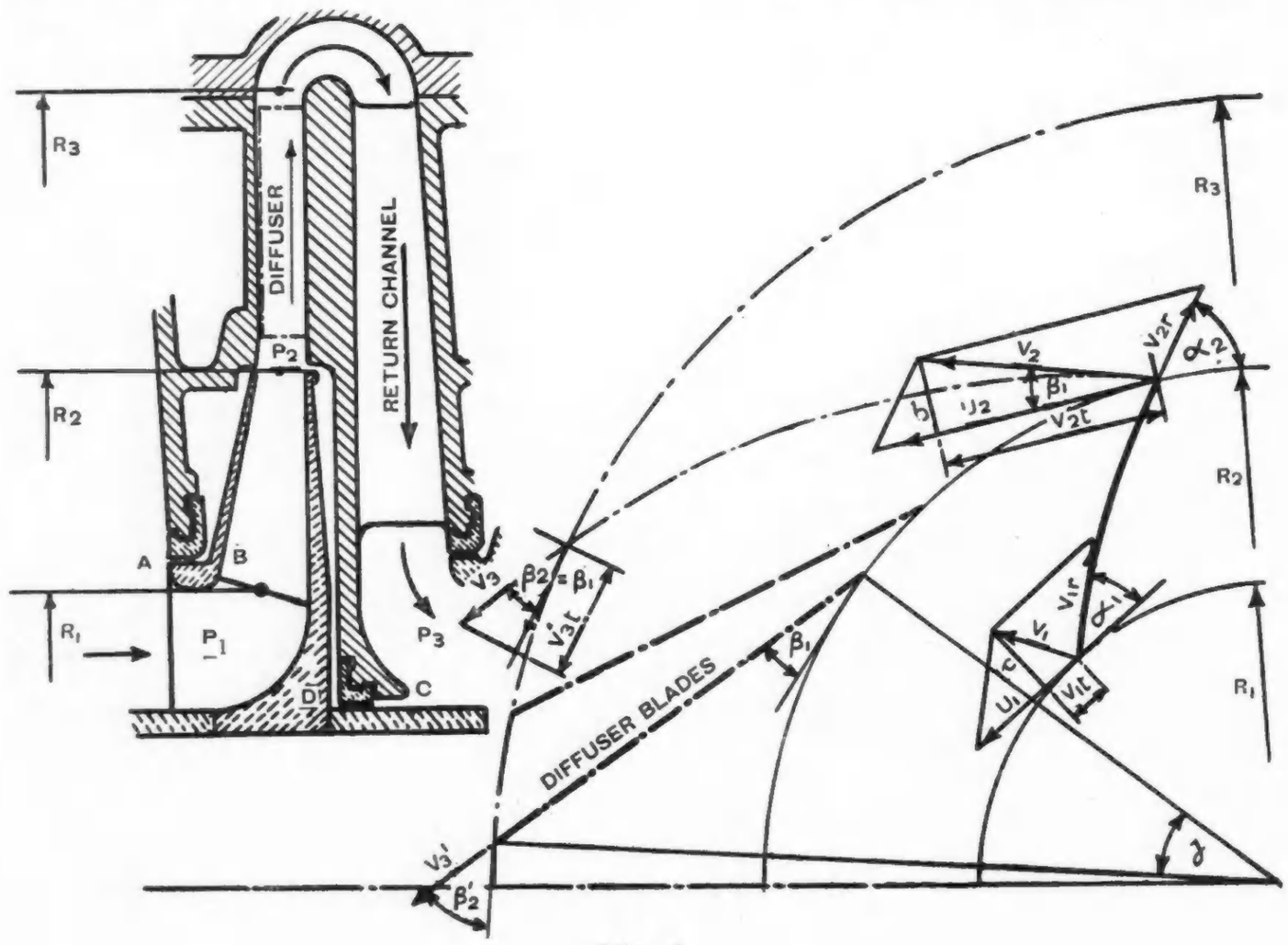


Fig. 1.

$$(1) \qquad N = \frac{1}{g}\left(V_{2t}\,u_2 - V_{1t}\,u_1\right)$$

where N = power input in ft. lbs./sec.

g = acceleration due to gravity in ft/sec.^{2}

V_{2t} = tangential component in ft./sec. of the absolute gas velocity V_2 at the impeller outlet.

V_{1t} = tangential component in ft./sec. of the absolute gas velocity V_1 at the impeller inlet.

V_{2t} and V_{1t} are to be taken as positive quantities if their direction coincides with the direction of peripheral velocity, otherwise they are to be given negative sign.

u_2 and u_1 = peripheral velocity in ft./sec. at the impeller outlet and inlet respectively.

This power input is equal to the amount of kinetic energy K_s ft. lbs./sec. acquired by 1 lb. of gas per sec. passing through an impeller.

$$(2) \qquad N = K_s = \frac{1}{g}\left(V_{2t}\, u_2 - V_{1t}\, u_1 \right)$$

From fig. 1 we find:

$$c^2 = V_1^2 - V_{1t}^2 = V_{1r}^2 - \left(u_1 - V_{1t} \right)^2$$
$$= V_{1r}^2 - u_1^2 + 2u_1 V_{1t} - V_{1t}^2$$
$$\text{and } u_1 V_{1t} = \frac{V_1^2 - V_{1r}^2 + u_1^2}{2}$$

$$\text{Similarly: } b^2 = V_2^2 - V_{2t}^2 = V_{2r}^2 - \left(u_2 - V_{2t} \right)^2$$
$$\text{and } u_2 V_{2t} = \frac{V_2^2 - V_{2r}^2 + u_2^2}{2}$$

V_{1r} and V_{2r} being relative gas velocities in ft./sec. at the impeller inlet and outlet respectively.

The equation (2) can now be written in the following form:—

$$(3) \quad N = K_s = \frac{1}{2g}\left[V_2^2 - V_1^2 + V_{1r}^2 - V_{2r}^2 + u_2^2 - u_1^2 \right]$$

For the axial type $u_2 = u_1 = u$ and equations (2) and (3) become:

$$(2a) \quad N = K_s = \frac{1}{g}\, u \left(V_{2t} - V_{1t} \right)$$

$$(3a) \quad N = K_s = \frac{1}{2g}\left[V_2^2 - V_1^2 + V_{1r}^2 - V_{2r}^2 \right]$$

For the radial type we derive from Fig. 1.

$$V_{2t} = u_2 - V_{2r} \cos \alpha_2$$
$$\text{and } V_{1t} = u_1 - V_{1r} \cos \alpha_1$$

Let A_1 = effective cylindrical area in sq. ft. at the impeller inlet.

A_2 = effective cylindrical area in sq. ft. at the impeller outlet.

Q_1 = gas flow in cb. ft./sec. at the impeller inlet.

v_1 = specific volume of gas in cb. ft./lb. at the impeller inlet.

v_2 = specific volume of gas in cb. ft./lb. at the impeller outlet.

$$\text{Then } V_{1r} = \frac{Q_1}{A_1 \sin \alpha_1}$$

$$\text{and } V_{2r} = \frac{Q_1 \frac{v_2}{v_1}}{A_2 \sin \alpha_2}$$

and the equation (2) becomes:

$$(4) \qquad N = K_s = \frac{1}{g}\left[u_2 \left(u_2 - V_{2r} \cos \alpha_2 \right) - u_1 \left(u_1 - V_{1r} \cos \alpha_1 \right) \right]$$
$$= \frac{1}{g}\left[u_2^2 - u_1^2 + Q_1 \left(\frac{u_1 \cot \alpha_1}{A_1} - \frac{u_2 \frac{v_2}{v_1} \cot \alpha_2}{A_2} \right) \right]$$

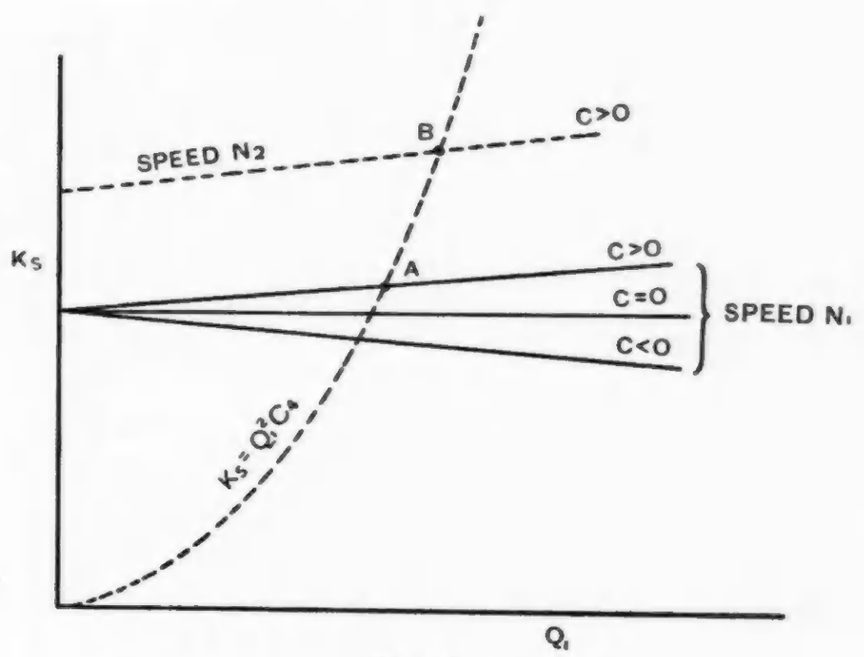


Fig. 2.

For a given impeller at a given speed n_1, u_2, A_2, α_2, u_1, A_1 and α_1 are constants, and $\frac{v_2}{v_1}$ varies slightly with Q_1 (though in the special design with $V_{1r} = V_{2r}$ it is constant); neglecting this slight variation of $\frac{v_2}{v_1}$ we can write approximately:

$$(5) \qquad K_s = \frac{1}{g}\left(u_2^2 - u_1^2 \right) + \frac{1}{g}\, Q_1\, C;$$

C being a constant and $= \dfrac{u_1 \cot \alpha_1}{A_1} - \dfrac{u_2 \frac{v_2}{v_1} \cot \alpha_2}{A_2}$

Plotting K_s as ordinates with Q_1 as abscissae the equation (5) will be represented by a straight line.

For $Q_1 = O$, $K_s = \frac{1}{g}\left(u_2^2 - u_1^2 \right)$; the line will be ascending if C is a positive quantity, or descending if C is a negative quantity, or horizontal if $C = O$ (see fig. 2).

For an axial type $u_2 = u_1 = u$ and the equation (4) becomes:

$$(4a) \quad K_s = \frac{1}{g}\, Q_1\, u \left(\frac{\cot \alpha_1}{A_1} - \frac{\frac{v_2}{v_1} \cot \alpha_2}{A_2} \right)$$

For a given axial impeller running at a given speed, and neglecting the slight variation of $\frac{v_2}{v_1}$, K_s plotted as ordinates against Q_1 as abscissae appears (see fig. 3) as a straight line ; for $Q_1 = O$, $K_s = O$, and we see a marked difference between the radial and axial types.

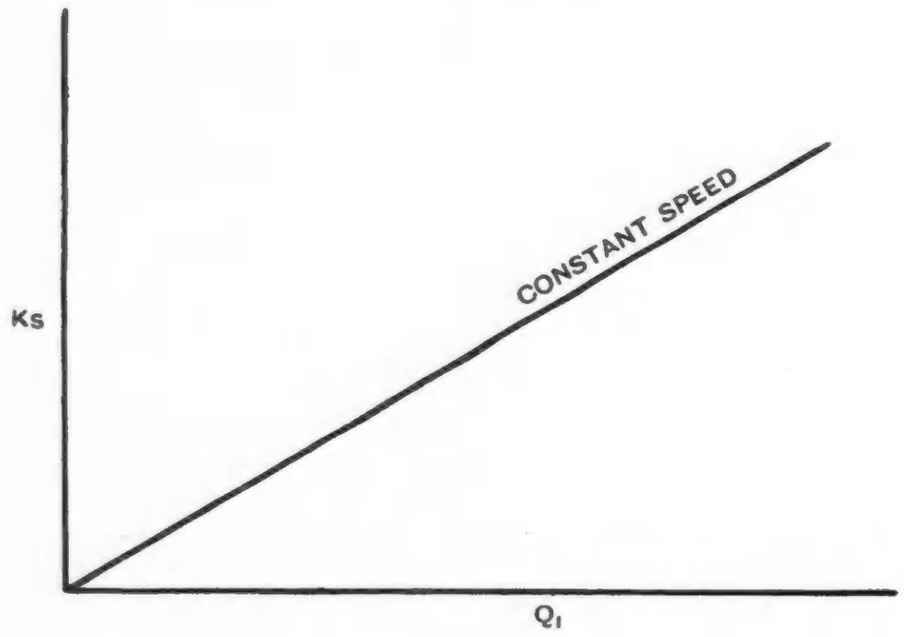


Fig. 3.

Reverting to the equation (4) for the radial type, for a given impeller $\frac{u_1}{u_2} = a$ is constant and we can write :

$$K_s = \frac{1}{g}\left[u_2^2\left(1 - a^2\right) + Q_1 u_2 \left(\frac{a \cot \alpha_1}{A_1} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{A_2}\right)\right]$$

Neglecting the variation of $\frac{v_2}{v_1}$, for a given impeller

$$\frac{a \cot \alpha_1}{A_1} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{A_2} = C_1 \text{ is practically}$$

constant and

$$(6) \qquad K_s = \frac{1}{g}\left[u_2^2\left(1 - a^2\right) + Q_1 u_2 C_1\right]$$

We see from this equation that K_s will not increase proportionately to the square of the speeds for given gas quantities as is frequently assumed, and in fig. 2 the dotted line indicates K_s for increased speed corresponding to the full ascending line ; the dotted line is steeper.

Equation (6) can be written as follows :

$$(7) \qquad K_s = \frac{1}{g} u_2^2 \left[1 - a^2 + \frac{Q_1}{u_2} C_1\right]$$

which shows that if the gas flow is increased proportionately to the speed, K_s will increase proportionately to the square of the speed. The increase of the gas flow proportionate to increased speed is expressed by

$$(8) \qquad \frac{Q_1}{u_2} = C_2 \text{ (constant).}$$

From (7) we obtain

$$K_s = \frac{1}{g} u_2^2 \left[1 - a^2 + C_1 C_2\right]$$

$$\text{Let } C_3 = 1 - a^2 + C_1 C_2$$

$$\text{then } K_s = \frac{1}{g} u_2^2 C_3 ;$$

we have from (8)

$$Q_1^2 = C_2^2 u_2^2$$

and combining the last two equations we obtain

$$(9) \qquad K_s = \frac{Q_1^2 C_3}{C_2^2 g} = Q_1^2 C_4$$

(C_4 being a constant) which expresses the condition

$$\frac{Q_1}{u_2} = C_2.$$

Equation (9) is a parabolic curve from the origin of the co-ordinate system in fig. 2.
The K_s at points A and B of intersection of the curve $K_s = Q_1^2 C_4$ and the lines K_s for the same C, and speeds n_2 and n_1 will be

$$(10) \qquad K_s^B = K_s^A \times \frac{n_2^2}{n_1^2}$$

The factor C_1 in the equation (7)

$$C_1 = \frac{a \cot \alpha_1}{A_1} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{A_2}$$

can be expressed as follows :

$$C_1 = \frac{a \cot \alpha_1}{C_5 D_2^2} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{C_6 D_2^2}$$

when C_5 and C_6 are constants for a given impeller and D_2 its outside diameter ; the equation (7) can be transformed into :

$$K_s = \frac{1}{g} u_2^2 \left[1 - a^2 + \frac{Q_1}{u_2 D_2^2}\left(\frac{a \cot \alpha_1}{C_5} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{C_6}\right)\right]$$

Neglecting the slight variation of $\frac{v_2}{v_1}$ we write

$$\frac{a \cot \alpha_1}{C_5} - \frac{\frac{v_2}{v_1}\cot \alpha_2}{C_6} = C_7 \text{ (a constant)}$$

and $$K_s = \frac{1}{g} u_2^2 \left[1 - a_2 + \frac{Q_1}{u_2 D_2^2} C_7\right]$$

Let $\frac{Q_1}{u_2 D_2^2} = \delta$ which we will call the volumetric

coefficient ; then

$$(11) \qquad K_s = \frac{1}{g}\, u_2^2 \left[1 - a^2 + \delta\, C_7\right]$$

K_s depends on u_2^2 and δ , a and C_7 being constants determined by the dimensions of the impeller.

If we introduce the co-efficient $\mu_t = \dfrac{K_s}{\dfrac{u_2^2}{g}}$, we obtain

$$(12) \qquad \mu_t = 1 - a^2 + \delta\, C_7.$$

For geometrically similar impellers a and C_7 have the same value, hence the value of μ_t for any given value of δ will be the same for all geometrically similar impellers.

It will be seen later on that for judging the actual performance of a stage it is convenient to split K_s in three separate parts indicated by the equation (3)

$$K_s = K_u + K_v + K_{vr}$$

when
$$K_u = \frac{1}{2g}\left(u_2^2 - u_1^2\right)$$

$$K_v = \frac{1}{2g}\left(V_2^2 - V_1^2\right)$$

$$K_{vr} = \frac{1}{2g}\left(V_{1r}^2 - V_{2r}^2\right)$$

We will consider a given impeller running at a constant speed with varying gas flow Q_1 ; u_2 and u_1 are entirely independent from Q_1 ; on the other hand it can be seen from the velocity diagram in fig. 1 that V_1 , V_2 , V_{1r} and V_{2r} will vary with Q_1. An example is given in fig. 4 ; the calculations have been made taking into account the variation of $\dfrac{v_2}{v_1}$, hence the curve for K_s is not quite a straight line as indicated by some of our approximate equations. From fig. 4, we see the variation of K_v and K_{vr} with varying Q_1 ; that there is an inter-relation between these two quantities is evident when we realize (see velocity diagram in fig. 1) that

$$V_2^2 = u_2^2 + V_{2r}^2 - 2u_2\, V_{2r} \cos \alpha_2$$

$$V_1^2 = u_1^2 + V_{1r}^2 - 2u_1\, V_{1r} \cos \alpha_1$$

$$\text{or } K_v = K_u - K_{vr} - 2u_2\, V_{2r} \cos \alpha_2 + 2u_1\, V_{1r} \cos \alpha_1.$$

It should be borne in mind that the kinetic energies in fig. 4 and in our equations refer to a gas quantity of 1 lbs./sec. The total kinetic energy imparted by the impeller to the actual gas quantity flowing through the impeller per sec. will therefore be :

$K_s \dfrac{Q_1}{v_1}$ and this is shown in fig. 4 by a dotted line (with an assumption that the maximum quantity shown on the diagram $Q_1^{\max}$ corresponds to 2 lbs./sec.).

(*b*) **CONVERSION OF KINETIC ENERGY.**

Having examined the first part of the principle of operation, namely the kinetic energy imparted to the gas by the impeller, we can proceed to the second part, the conversion of the kinetic energy into heat energy. Such conversion is represented by the well known equation referring to 1 lb./sec. of gas :

$$-dK = \frac{1}{g}\, d\left(\frac{V^2}{2}\right) = 1\, v\, dP$$

where K = kinetic energy in ft. lbs./sec.

v = specific volume in cu. ft./lb.

P = pressure in lbs./sq. ft.

or integrating we obtain :

$$(13) \qquad \int_{K_1}^{K_2} -dK = \int_{P_1}^{P_2} v\, dP$$

where K_1 is the kinetic energy of 1 lb. of gas before conversion, $K2$ after conversion.

P_1 is the gas pressure at inlet to the stage

P_2 at the outlet.

If the absolute gas velocity at the outlet of the stage is equal to the absolute gas velocity at the inlet, then the kinetic energy imparted to the gas by the impeller is completely converted into heat energy ;

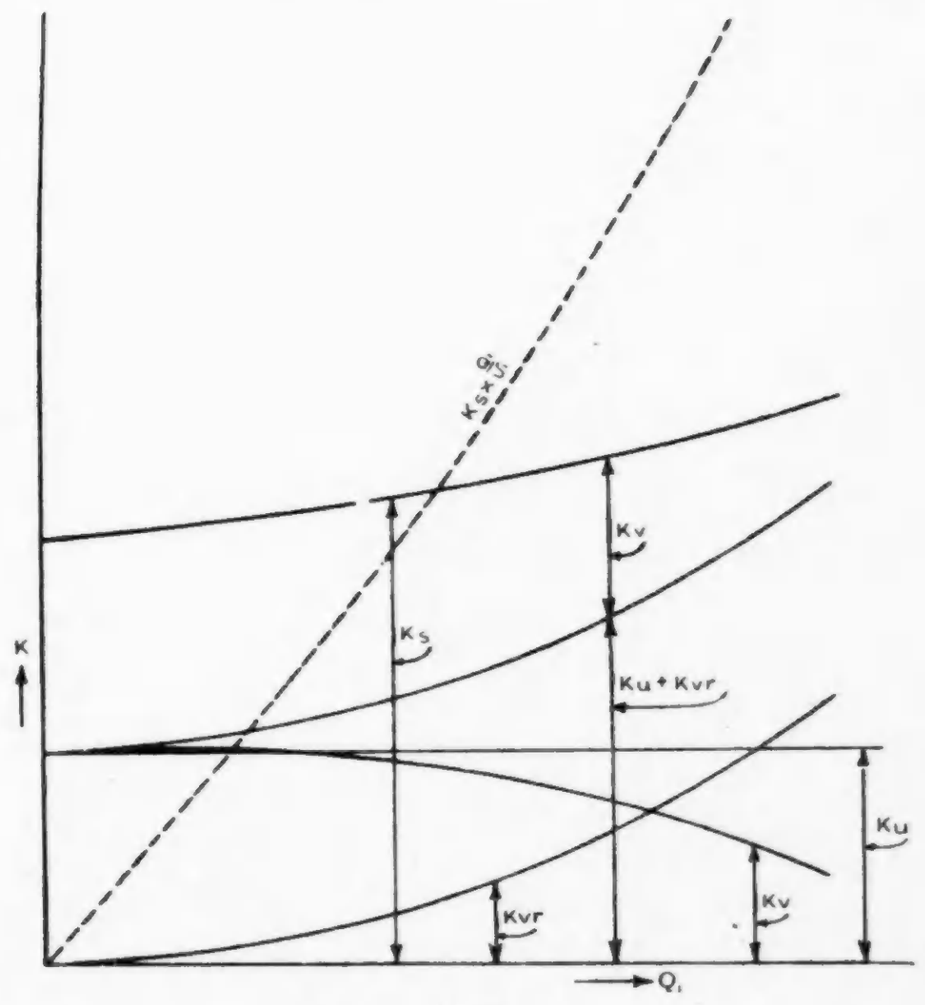


Fig. 4.

such condition is often fulfilled in multi-stage machines as the absolute inlet velocities of two following stages can be made the same, and for our purposes we shall consider a stage including the impeller, the diffuser with the return channel to the inlet of the next impeller.

Equation (13) becomes

$$\int_{K_1}^{K_2} -dK = K_1 - K_2 = K_s = \int_{P_1}^{P_2} v\,dP$$

For small pressure differences the specific volume may be taken as constant and we have:

$$K_s \cong v\left(P_2 - P_1\right) = \frac{P_2 - P_1}{\gamma}$$

γ being specific weight in lbs./cu. ft.
For larger pressure differences v should be taken as a function of pressure.

We will now assume an ideal stage without any losses, such as friction, eddies, shocks, leakage and without heat interchange with the surrounding neighbourhood. In such ideal stage the energy conversion would be adiabatic; in other words the pressure and specific volume of the gas have the relation

$$Pv^k = C = \text{constant}$$

$$\text{or } v = C' P^{-\frac{I}{k}}$$

$$\int_{P_1}^{P_2} v dP = \int_{P_1}^{P_2} C' P^{-\frac{I}{k}} d P = \frac{C' k}{k-1}\left[P_2^{\frac{k-I}{k}} - P_1^{\frac{k-I}{k}}\right]$$

$$= P_1 v_1 \frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-I}{k}} - 1\right]$$

which is of course the work required for adiabatic compression of 1-lb. of gas or the power input in ft. lb./sec. necessary for adiabatic compression of 1-lb. of gas per sec.

$$(15)\ K_s = P_1 v_1 \frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-I}{k}} - 1\right]$$

As $P_1 v_1 = RT_1$; $k = \frac{c_p}{c_v}$; $\left(\frac{P_2}{P_1}\right)^{\frac{k-I}{k}} = \frac{T_2}{T_1}$;

$A R = c_p - c_v$ we obtain:

$$(16)\ K_s = \frac{1}{A} c_p \left(T_2 - T_1\right)$$

in which c_p = specific heat at constant pressure.

T_2 = absolute temperature at end of compression °F.

T_1 = initial absolute temperature °F.

The total heat of 1-lb. of gas being given by $c_p T$ we see that the converted kinetic energy expressed in equivalent heat value is equal to the increase of total heat of gas. One B.Th.U. is equivalent to a mechanical energy of 778 ft. lbs. and this constant is usually designated as

$$\frac{1}{A} = 778 \text{ ft. lb.}$$

The equation is of course applicable to each of the parts of kinetic energy K_u, K_v and K_w and we would obtain for each part separately partial pressure rises or partial increases of the total heat.

In the actual stage there are losses F_s due to friction, shocks, eddies and leakage; these losses F_s will take a certain amount of kinetic energy and be converted into heat which will act in the same way as if that heat had been supplied from an outside source; *i.e.* the gas will be heated without pressure increase (heat supplied at constant pressure). That part of the kinetic energy not taken by the losses will be converted into work of adiabatic compression; in other words

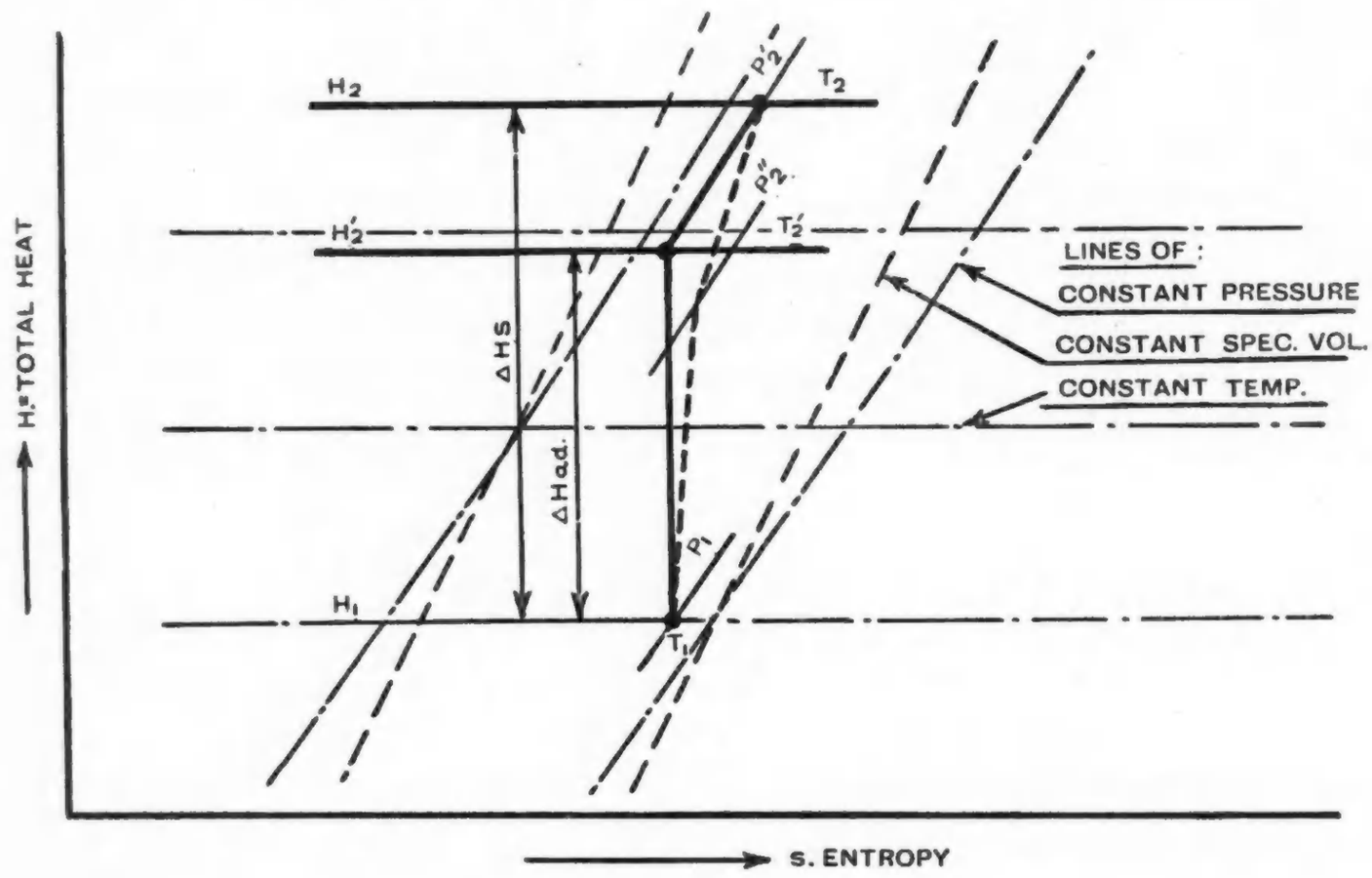


Fig. 5.

$$K_s - F_s = P_1 v_1 \frac{k}{k-1}\left[\left(\frac{P_2'}{P_1}\right)^{\frac{k-1}{k}} - 1\right] = \frac{1}{A} c_p \left(T_2' - T_1\right)$$

when of course P_2' and T_2' will be lower than P_2 and T_2 in equation (16).

The losses F_s heat the gas at the pressure P_2'

$$F_s = \frac{1}{A} c_p \left(T_2 - T_2'\right)$$

when T_2 is identical with T_2 in equation (16). The kinetic energy reappears in the gas as the increase of its total heat. By hydraulic efficiency of a stage η_h we shall understand the ratio

$$\eta_h = \frac{K_s - F_s}{K_s} = \frac{T_2' - T_1}{T_2 - T_1}$$

The specific heat of gas varies slightly with temperature; hence we should write correctly

$$K_s = \frac{1}{A}\left(c_{p2} T_2 - c_{p1} T_1\right).$$

The formula (15) is rather complicated, involving the calculation of pressures, specific volumes and temperatures, and it is found of advantage to construct a (Total heat—Entropy) diagram for a gas which is frequently considered. A small portion of such diagram is shown in fig. 5.

The Entropy s is defined by:

$$ds = \frac{d\,H}{T}$$

where $d\,H$ is the heat to be supplied or abstracted at the absolute temperature T.

For adiabatic change of state $d\,H = o$; consequently

$$s = \int ds = \int \frac{d\,H}{T} = O + \text{constant.}$$

In our Entropy diagram the adiabatic change of state is shown as a vertical line s = constant between the initial and final pressures. The losses appear as heat added at constant pressure.

For our stage we obtain for adiabatic compression

$$\eta_h AK_s = H_2' - H_1$$

and the heat due to losses is

$$(1 - \eta_h) AK_s = H_2 - H_2'$$

Hence $AK_s = H_2 - H_1 = \Delta H_s$

where ΔH_s = the increase of total heat of gas in our stage, in B.Th.U/sec.; or, since we refer to 1 lb./sec. of gas, in B.Th.U/lb.

The whole process is shown in fig 5; from the initial pressure P_1 and temperature T_1 (total heat H_1) an adiabatic increase in total heat $H_2' - H_1 = \eta_h AK_s$ reaches the pressure P_2' and temperature T_2'; the point of intersection of the pressure line P_2' and the line of total heat $H_2 = H_1 + \Delta H_s = H_1 + AK_s$ gives the state of gas at the outlet of the stage P_2', T_2.

It is expedient to consider the conversion of kinetic energy into heat energy in two steps. Referring to the equation (3) we see that K_s is made up of three parts:

(a) one arising out of the change of absolute velocity V and obviously this part of kinetic energy will be converted into heat energy in the diffuser and the return channel to the next stage (it is assumed that the absolute inlet velocity in the next stage is the same as in the stage under consideration);

(b) one arising out of the change of relative velocity in the impeller V_r and

(c) one arising out of the change of peripheral velocity at the impeller inlet and outlet. The two parts under (b) and (c) will be naturally converted into heat energy in the impeller itself.

$$\text{Let } \frac{A}{2g}\left(V_2^2 - V_1^2\right) = \Delta H_d$$

$$\frac{A}{2g}\left(V_{1r}^2 - V_{2r}^2\right) = \Delta H_{vr}$$

$$\text{and } \frac{A}{2g}\left(u_2^2 - u_1^2\right) = \Delta H_u$$

$$\text{then } \Delta H_s = \Delta H_d + \Delta H_i$$

$$\text{and } \Delta H_i = \Delta H_{vr} + \Delta H_u$$

where ΔH_i = energy converted in the impeller.

In fig. 6 are plotted the velocities V, V_r and u for a stage in function of the gas flow Q_1 (in cu. ft./sec.) when the impeller is kept at a constant speed. It will be realized at once that there are no losses in kinetic energy on account of the peripheral velocities and that part of the kinetic energy will be converted adiabatically into heat energy.

The losses in the impeller may be conveniently corelated to the relative velocity V_r. From fig. 6 we see that with increasing gas flow V_{1r} increases proportionately while V_{2r} increase is not substantially different from the proportionate increase. The losses on kinetic energy in the impeller may be expressed as

$$\zeta_1 \frac{V_{1r}^2}{2g} = F_i$$

the coefficient ζ_1 being dependent slightly on V_{1r}. These losses in the impeller will depend not only on its shape, but also on its dimensions; two geometrically similar impellers will have different losses, smaller impeller having greater loss for the same volumetric coefficient δ.

The gas flow leaving the impeller and entering the diffuser is exposed to leakage loss at the periphery of the side plate of the impeller, to injection loss at

the periphery of the main impeller disc, in the diffuser itself and the return channel to friction, shocks and eddies. From fig. 6 we see that V_2 varies between comparatively small limits over the range of Q_1 shown on the diagram; on the other hand there is a considerable variation of V_1; the nature of the losses in the diffuser is, therefore, very complicated. Two cases should be considered:

(a) diffuser without guide blades and

(b) diffuser with guide blades.

The relation expressed by the equation (1) is applicable also on the diffuser, except, of course, that the gas flows freely through the diffuser without doing any mechanical work; with reference to fig. 1

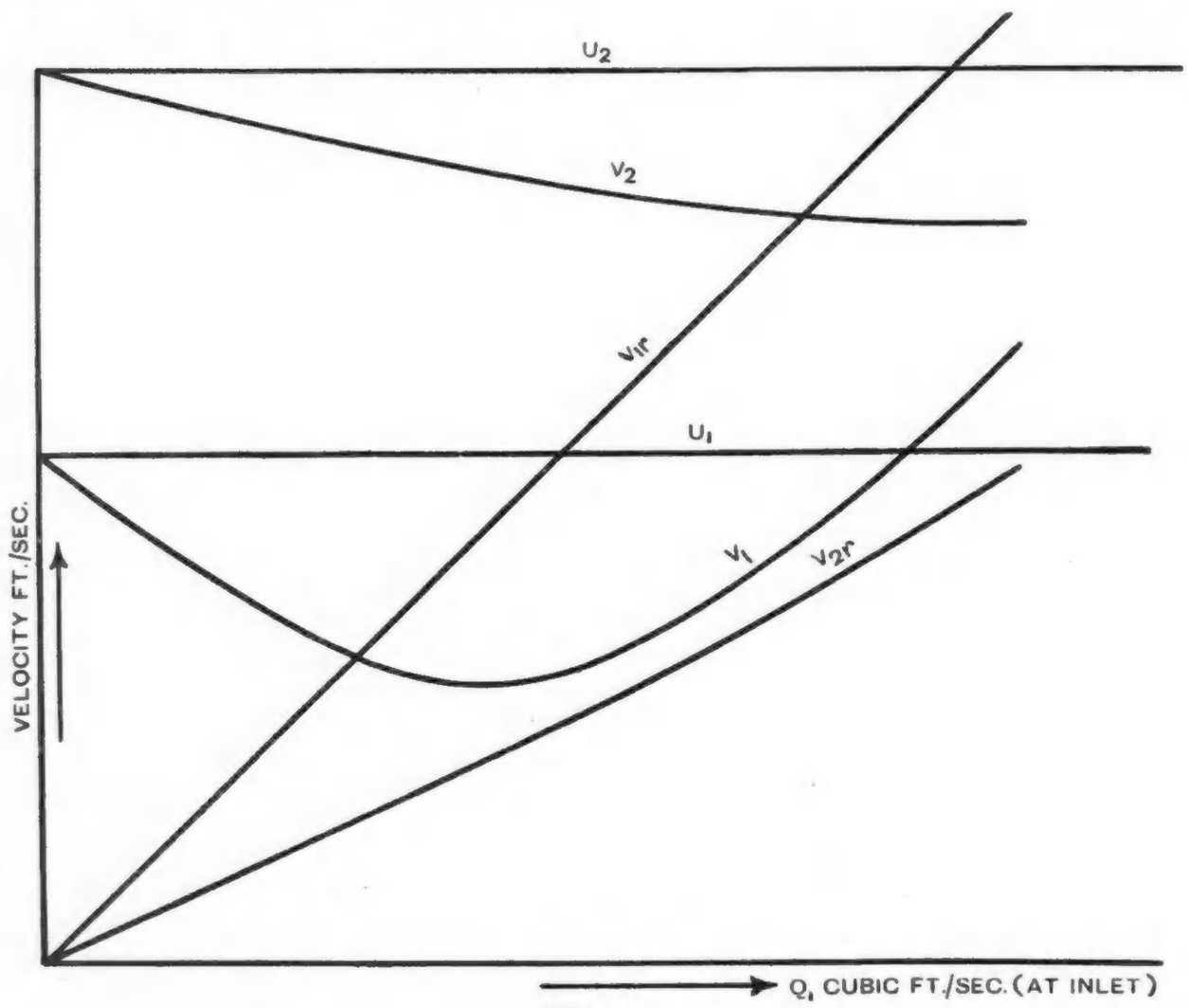


Fig. 6.

we have, if M is the turning moment in lbs.-ft. and ω is the angular velocity in radians per second:

$$N = O = \frac{1}{g}\left(V_{2t}\, u_2 - V_{3t}\, u_3\right) = M\,\omega$$

$$= \frac{1}{g}\ \omega\ \left(V_{2t}\, R_2 -, V_{3t}\, R_3\right)$$

$$\text{or } M = \frac{1}{g}\left(V_{2t}\, R_2 - V_{3t}\, R_3\right)$$

In a diffuser without guide glades no turning moment can possibly arise, hence:

$$M = O \text{ and } \quad V_{2t}\, R_2 - V_{3t}\, R_3 = O$$

$$\text{or } \ V_{3t} = \frac{R_2}{R_3}\, V_{2t}$$

In other words, the tangential component of the absolute velocity in the diffuser without guide blades decreases proportionately with the increasing radius; the radial component will decrease with increasing cylindrical area (if we neglect the small change of the specific volume) and therefore, in a diffuser with parallel radial walls, with increasing radius. If both the tangential and radial components of the absolute velocity decrease with increasing radius, the angle of the absolute velocity at any point of the diffuser is the same (assuming the losses are not different for the tangential and the radial component) or in fig. (1)

$$\beta_1 = \beta_2$$

With a diffuser with guide blades such as shown in fig. 1.

$$\beta_2' + 90^\circ = \beta_1 + 90^\circ + \gamma$$

$$\beta_2' = \beta_1 + \gamma$$

As $\beta_1 < 90^\circ$, γ is positive, hence $\beta_2' > \beta_1$;

$$V_3 = \frac{Q_3}{A_3 \sin \beta_1} \text{ - - - - - without diffuser blades.}$$

$$V_3' = \frac{Q_3'}{A_3 \sin (\beta_1 + \gamma)} \text{ - - - - with diffuser blades.}$$

A_3 being the cylindrical area at the diffuser outlet. It follows that $V_3' < V_3$, because $\beta_1 + \gamma > \beta_1$, and incidentally that $Q_3' < Q_3$, because the gas is more compressed by virtue of V_3' being $< V_3$.

In the diffuser itself the converted kinetic energy will be: $\frac{1}{2g}\left(V_2^2 - V_3^2\right)$ without diffuser blades

and $\frac{1}{2g}\left(V_2^2 - V_3'^2\right)$ with diffuser blades;

as V_3' is smaller than V_3 the losses in the curved

channel connecting the diffuser to the return channel are also smaller; on the whole with diffuser blades we convert more of the available kinetic energy adiabatically into heat energy than without diffuser blades; for substantially increased or reduced gas flow from the designed quantity the angle of the diffuser blades at inlet is respectively too small or too large and therefore at too large or too small duties there will be appreciable shock losses. Moreover for larger duty the inlet area of the diffuser with guide blades is too small and the gas compressed in the impeller will have to re-expand; from an increased certain duty upwards the angle β_1 and β_2 will be obtained by diffuser blades over a certain range of gas flow.

The characteristic curves $K_s - F_s$ and $K_s - F_s'$ become horizontal at a certain smaller duty, and then decrease for still smaller duties; from the summit of these curves down to smaller duties the gas flow becomes unstable, and the gas surges; for stable operation only the descending part of the characteristic curve is useful. We see in particular that the operating range is reduced by diffuser blades. It may be also noted that at a certain large duty the losses in the diffuser and return channel F_d become greater than K_v; in other words the excess losses

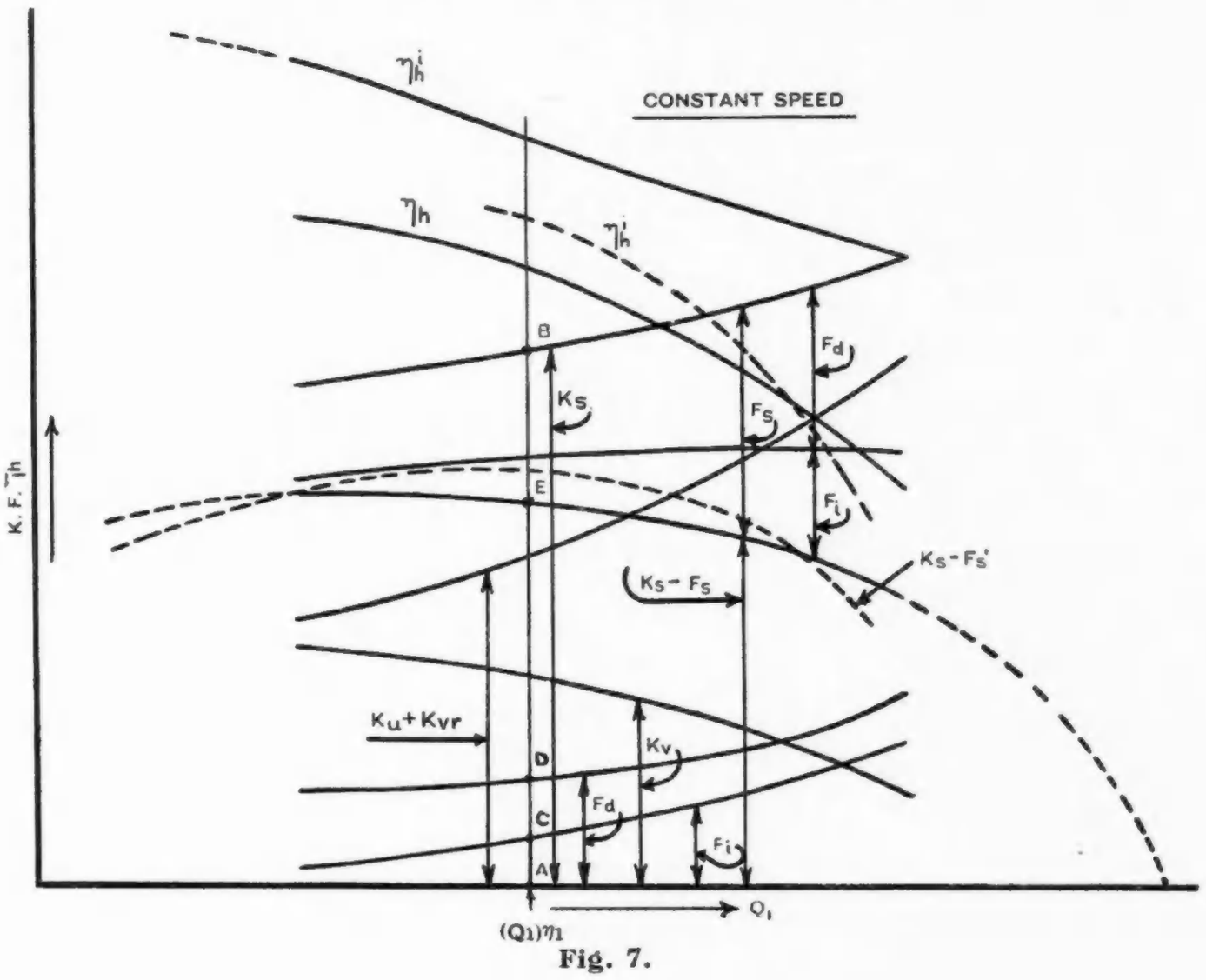


Fig. 7.

actually greater than β_2'; hence V_3' will be $> V_3$ and the diffuser without blades will become more effective.

In fig. 7 are plotted the kinetic energies K_v, $K_u + K_{vr}$ and K_s, which are related by

$$K_s = K_v + K_u + K_{vr}$$

and the losses F_i in the impeller

F_d in the diffuser and return channel

$$F_i + F_d = F_s;$$

further a curve $K_s - (F_i + F_d) = K_s - F_s$ for bladeless diffuser and a curve $K_s - F_s'$ for diffuser with guide blades.

The hydraulic stage efficiencies $\eta_h = \dfrac{K_s - F_s}{K_s}$ (without diffuser blades) and $\eta_h' = \dfrac{K_s - F_s'}{K_s}$ (with diffuser blades) are also plotted and show the improvement have to be covered by partial re-expansion of gas compressed in the impeller, until at some high duty no adiabatic compression work is obtained, $K_s - F_s$ becoming O.

It will be seen that the hydraulic efficiency for the impeller alone $\eta_h^i = \dfrac{K_u + K_{vr} - F_i}{K_u + K_{vr}}$ is substantially higher than that of the whole stage (see fig. 7), which is of course due to the fact that K_u (see fig. 4) is converted in heat energy adiabatically; this particular factor causes the radial type to be more efficient than the axial type.

The stage operating at a speed n_1 for which the fig. 7 gives full operating details may now be examined for speed n_2; for a given gas flow $(Q_1)_{n1}$ and speed n_1 we have

$$K_s = \overline{AB}$$

$F^i = \overline{AC}$; $F_d = \overline{AD}$ and $K_s - F_s = \overline{AE}$

If we change the speed to n_2 and, at the same time, the gas flow to $\left(Q_1 \right)_{n1} \times \frac{n_2}{n_1}$, we have

$$\left(u_2\right)_{n2} = \left(u_2\right)_{n1} \times \frac{n_2}{n_1}\,; \quad \left(u_1\right)_{n2} = \left(u_1\right)_{n1} \times \frac{n_2}{n_1}$$

$$\left(V_2\right)_{n2} = \left(V_2\right)_{n1} \times \frac{n_2}{n_1}\,; \quad \left(V_1\right)_{n2} = \left(V_1\right)_{n1} \times \frac{n_2}{n_1}$$

$$\left(V_{2r}\right)_{n2} = \left(V_{2r}\right)_{n1} \times \frac{n_2}{n_1}\,; \quad \left(V_{1r}\right)_{n2} = \left(V_{1r}\right)_{n1} \times \frac{n_2}{n_1}$$

$$\text{Therefore } \left(K_s\right)_{n2} = \left(K_s\right)_{n1} \times \frac{{n_2}^2}{{n_1}^2}$$

It should be noted that the direction of the gas velocities remains unaltered, and the losses will be approximately proportional to the square of velocities, or to the square of the gas flow; hence

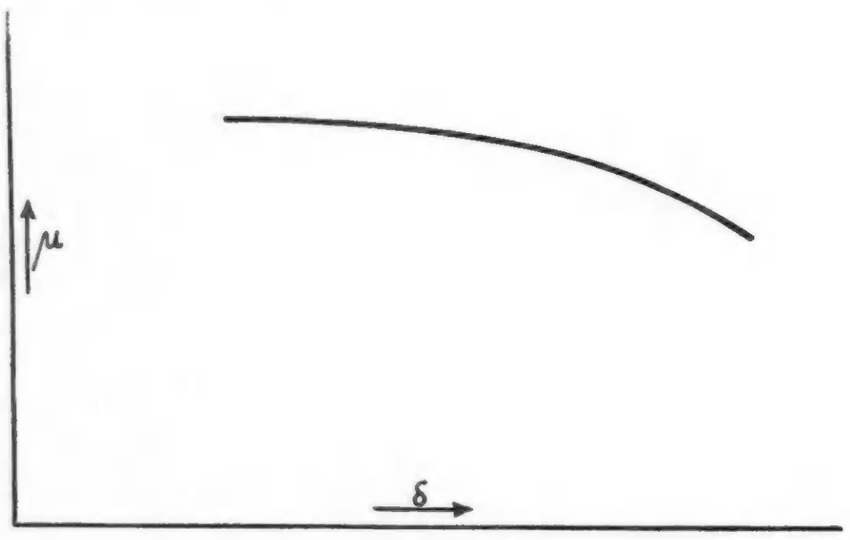


Fig. 8.

$$\left(F_i\right)_{n2} = \left(F_i\right)_{n1} \times \frac{{n_2}^2}{{n_1}^2} \text{ and } \left(F_d\right)_{n2} = \left(F_d\right)_{n1} \times \frac{{n_2}^2}{{n_1}^2}$$

$$\text{therefore } \left(K_s - F_s\right)_{n2} = \left(K_s\right)_{n1} \frac{{n_2}^2}{{n_1}^2} - \left(F_s\right)_{n1} \frac{{n_2}^2}{{n_1}^2}$$

$$= \left(K_s - F_s\right)_{n1} \frac{{n_2}^2}{{n_1}^2}$$

$$\text{as } \frac{{n_2}^2}{{n_1}^2} = \frac{{(u_2)_{n2}}^2}{{(u_2)_n}^2{}_1}$$

$$\left(K_s - F_s\right)_{n2} = \left(K_s - F_s\right)_{n1} \times \frac{{(u_2)_n}^2{}_2}{{(u_2)_n}^2{}_1}$$

The hydraulic efficiency for n_2 and $(Q_1)_{u1} \times \frac{n_2}{n_1}$

$$\left(\eta_h\right)_{n2} = \frac{\left(K_s - F_s\right)_{n1} \times \frac{(u_2)^2_{n2}}{(u_2)^2_{n1}}}{\left(K_s\right)_{n1} \times \frac{(u_2)^2_{n2}}{(u_2)^2_{n1}}} = \left(\eta_h\right)_{n1}$$

Thus if the speed and the gas flow are changed proportionately the hydraulic efficiency remains unaltered.

We see also that

$$\frac{\left(K_s - F_s\right)_{n2}}{{(u_2)_{n2}}^2} = \frac{\left(K_s - F_s\right)_{n1}}{{(u_2)_{n1}}^2}$$

Let $\frac{K_s - F_s}{{u_2}^2 \frac{1}{g}} = \mu$ - - - - - manometric coefficient

$$\left(\mu\right)_{n2} = \left(\mu\right)_{n1} \text{ when}$$

$$\left(Q_1\right)_{n2} = \left(Q_1\right)_{n1} \times \frac{n_2}{n_1}$$

which condition is fulfilled when the volumetric coefficient $\delta = \frac{Q_1}{u_2 {D_2}^2}$ is the same.

$K_s - F_s$ is equivalent to the adiabatic increase of the total heat ΔH_{ad} of 1 lb. of gas in one stage.

$$\frac{1}{A}\Delta H_{ad} = K_s - F_s$$

$$(17) \qquad \mu = \frac{\Delta H_{ad}}{A {u_2}^2 \frac{1}{g}}$$

$$\Delta H_{ad} = A P_1 v_1 \frac{k}{k-1}\left[\left(\frac{P_2'}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$$

$$(18) \qquad \mu = \frac{P_1 v_1 \frac{k}{k-1}\left[\left(\frac{P_2'}{P_1}\right)^{\frac{k-1}{k}} - 1\right]}{{u_2}^2 \frac{1}{g}}$$

In fig. 8 is plotted μ against δ; for any given value of δ we have a certain value of μ; for different duties (gas flow and pressure rise) we can readily calculate by means of the formula (17) or (18) and $\delta = \frac{Q_1}{u_2 {D_2}^2}$ the required speed.

In geometrically similar stages the percentage losses may be different; hence μ, though similar, may be also slightly different; but for a range of geometrically similar stages of dimensions not widely different the above formulae can be used for approximate calculations.

DISC FRICTION.

The impeller runs in a chamber formed by the stationary casing with a small clearance; the gas in this clearance space causes a loss of mechanical work by friction, the amount of this loss being given by the empirical formula:

$$N_r = \frac{8.5}{10^8} D^2 u^3 \gamma$$

where N_r = friction work in HP.
D = diameter of the impeller in ft.
u = peripheral velocity of the wheel in ft./sec.
γ = specific weight of the gas (surrounding the impeller) in lbs./cu. ft.

This friction work must be supplied to the impeller through the shaft from an outside power supply; it will be converted into heat energy taken up by the gas flow.

LEAKAGE LOSSES.

It is usual to use labyrinth packings to keep leakages within small limits. The gas pressure (see fig. 1) at A is the inlet pressure P_1; at B and D approximately the pressure P_2 at outlet of impeller, and at C the inlet pressure of the following impeller P_3; or across BA the pressure difference is $P_2 - P_1$, and across CD $P_3 - P_2$. Usually $P_2 - P_1$ is more than twice as great as $P_3 - P_2$, in addition the clearance diameter at AB is substantially greater, hence the leakage at AB is greater unless more effective packings are provided.

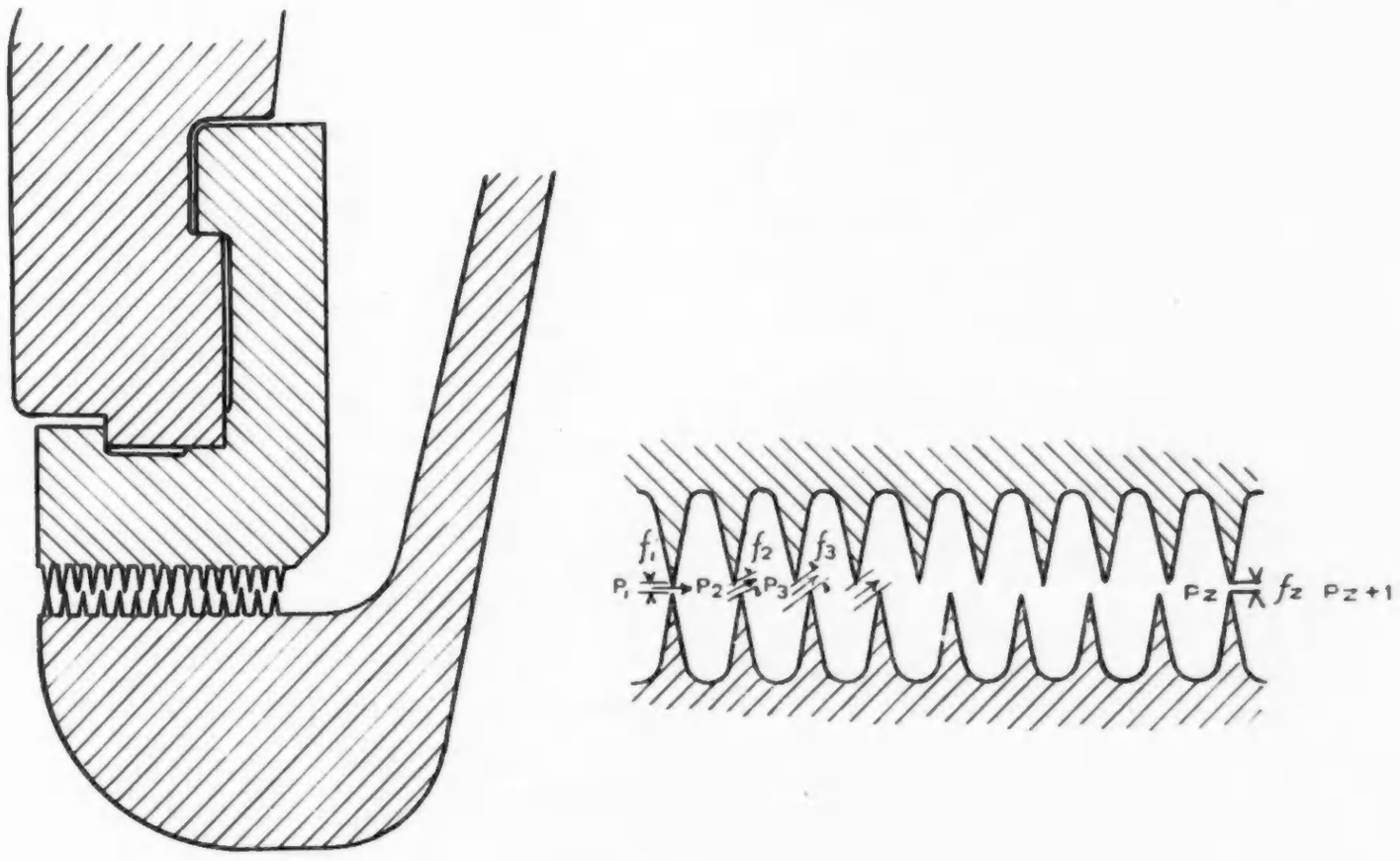


Fig. 9.

The action of a labyrinth is as follows (see fig. 9, symbols refer only to this figure). In the small clearance area f_1 in sq. ft. of one labyrinth ring the gas flows with an approximate velocity V_e given by the formula:

$$\frac{V_e^2}{2g} = -\int_{P_1}^{P_2} v\,dP = \bar{v}\left(P_1 - P_2\right) = \frac{P_1 - P_2}{\bar{\gamma}}$$

$$P_1 - P_2 = \frac{\bar{\gamma}}{2g}\ V_e^2$$

As $f_1 V_e = \frac{W}{\bar{\gamma}}$ W being the weight of leakage in lbs./sec.

$$V_e^2 = \left(\frac{W}{f_1}\right)\ \frac{1}{\bar{\gamma}^2}$$

and $$P_1 - P_2 = \frac{1}{2g}\left(\frac{W}{f_1}\right)^2 \frac{1}{\bar{\gamma}}$$

In the space after the first labyrinth clearance the velocity of gas is destroyed by shock, friction and eddies, no useful work being done; consequently the total heat of the gas, or its temperature, at inlet and outlet of one labyrinth stage is the same; therefore

$P_1 v_1 = \text{const} = P_2 v_2 = P_3 v_3$ etc. and we can then write

$$\frac{P_1 + P_2}{2}\ \bar{v} = P_1 v_1$$

$$P_1 - P_2 = \frac{1}{2g}\left(\frac{W}{f_1}\right)^2 \frac{2 P_1 v_1}{P_1 + P_2}$$

$$P_1^2 - P_2^2 = \frac{1}{g}\left(\frac{W}{f_1}\right)^2 P_1 v_1$$

As W is the same for all labyrinth clearances and

$P_1 v_1 = \text{constant}$,

we have

$$P_2^2 - P_3^2 = \frac{1}{g}\left(\frac{W}{f_2}\right)^2 P_1 v_1$$

and for the last rings z (z = total number of rings)

$$P_z^2 - P_{z+1}^2 = \frac{1}{g}\left(\frac{W}{f_z}\right)^2 P_1 v_1\ ;$$

adding up, we obtain

$$P_1^2 - P_{z+1}^2 = \frac{1}{g}\ W^2 P_1 v_1 \Sigma\left(\frac{1}{f^2}\right)$$

$$\text{or } W = \sqrt{\frac{\left(P_1^2 - P_{z+1}^2\right) g}{P_1 v_1 \Sigma\left(\frac{1}{f^2}\right)}}$$

or if we put $z\ \frac{1}{f_m^2} = \Sigma\left(\frac{1}{f^2}\right)$

$$W = f_m \sqrt{\frac{\left(P_1^2 - P_{z+1}^2\right) g}{P_1 v_1 z}}$$

P_1 and P_{z+1} being gas pressures before and after the packing, v_1 specific volume before the packing. In a special case when all labyrinth clearances f are

$$\text{equal then } \Sigma\left(\frac{1}{f^2}\right) = z\,\frac{1}{f^2}$$

$$f_m = f$$

$$\text{and } W = f\sqrt{\frac{(P_1^{\,2} - P_{z+1}^{\,2})\,g}{P_1\,v_1\,z}}$$

which is the well known formula, in which

W = leakage quantity in lbs./sec.
P = pressures in lbs./sq. ft.
v = specific volume in cu. ft./lb.
f = clearance area in sq. ft.

The leakage W_e round the inlet eye mixes with the gas at inlet impeller; the whole of the energy given to that leakage quantity in the impeller is converted into heat; in addition it has to be accelerated in the direction of the inflow, and hence it causes a further loss; the total loss appears as heat in the gas.

The leakage between the shaft and the diaphragm W_d causes a loss of more complicated nature: one part of the loss is represented by that portion of the kinetic energy imparted to the gas by the impeller, which is converted into pressure energy in the diffuser, and another part is represented by the energy necessary to entrain the leakage again into the diffuser. The loss, however, appears again as heat in the gas.

The main packings (at the inlet and outlet end of the machine) are generally made as labyrinth packings, or as combination of labyrinth and water packings, or other suitable liquid when it is necessary to prevent inhaling air into the gas at inlet or prevent gas escaping to atmosphere at the outlet.

The delivery packings are usually divided into two or more successive portions, the leak off being taken to successively lower stages of the machine. The importance of reduced leakage is self evident, not only in external, but also in internal packings; Fraser & Chalmers Engineering Works developed a special design (see figure 9); both the stationary as well as the rotating part are provided with rings with sharp edges; the pitch of the rings is quite small and therefore large number of rings can be provided in the restricted spaces, especially round the inlet eye of the impellers. The pitch is slightly different on the two parts; the result is that only very restricted number of rings in the whole packing can come accidentally in contact, and therefore only little heat is generated as a result of such contact; hence appreciable damage to the packing is practically excluded. The rotor moves axially relatively to the casing as a result of their different thermal expansions; in F. & C. packings such movement has no effect, as only the individual clearances change without changing the total effect of the packing.

COOLING.

The work required for adiabatic compression of 1 lb. of gas from P_1 to P_2 is $= P_1\,v_1\,\frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$

As $P_1\,v_1 = R\,T_1$ (R = gas constant) we see that for a given weight of gas the required compression work is proportional to the initial absolute temperature. In order to reduce the required work the gas temperature should be reduced by cooling. In low pressure machines the gas temperature is in any case comparatively low, and cooling in itself would produce little improvement; apart from that, in the case of machines used for smelting and delivering warm air, the heat in the air is not lost but in effect is fully utilized in the furnaces. For these reasons low pressure machines are as a rule uncooled.

For high pressure machines the temperature of gas becomes high, so for instance in an air compressor with 30″ Bar. 60° F. at inlet and 80 lbs. per sq. in. delivery pressure, the air temperature at the last stage would be in the neighbourhood of 520° F. or abs. temp. 979° F. in an uncooled machine; in a cooled machine the delivery temperature is in the neighbourhood of 170° F., absolute temperature about 630° F. The work required for the same pressure rise in the last stage in a cooled machine is $\frac{628}{978} = 64\%$ of the work in an uncooled machine. It might be mentioned that in an uncooled multi-stage machine the overall adiabatic efficiency is smaller than the adiabatic efficiency per stage, though the latter in all stages is the same; this is due to the reheat, or to all losses in the stage appearing as heat in the gas.

In a well cooled machine the compression process proceeds to a large extent between the adiabatic and isothermal change of state; in fact it is so near to the isothermal change that it has become a habit to compare the actual compression with the isothermal rather than adiabatic compression. The compression and cooling, though it may occur in part simultaneously, may be considered as two superposed operations.

The work W_{is} in ft.lb. required for isothermal compression of 1-lb. of gas from a pressure P_1 and specific volume v_1 to a pressure P_2 is given by:

$W_{is} = P_1\,v_1\,\log_e\frac{P_2}{P_1}$; the whole of this work represents the heat which has to be subtracted from the gas during the compression.

$$\text{As} \quad ds = \frac{dH}{T}$$

$$\text{We have} \quad H = T\,(s_1 - s_2) = A\,W_{is}$$

or $W_{is} = \frac{T}{A}(s_1 - s_2)$ and this can be quickly calculated with the aid of our Entropy diagram. To obtain delivery gas temperature t_2 equal to the inlet temperature t_1 it is necessary to abstract from the gas by cooling the heat quantity equivalent to the energy put into the shaft from which only the external losses (bearings, or auxiliary drives) are deducted; the external losses are almost negligible.

In actual practice, the delivery temperature t_2 of the gas will be higher than the inlet temperature, and therefore the abstracted heat quantity is smaller by the amount $c_p (t_2 - t_1)$ per 1 lb. of gas.

Assume an air turbo-compressor dealing with 13 lbs. of air per second and consuming 2,000 h.p., the inlet temperature being 60° F. and outlet temperature 170° F. Ignoring the negligible external losses, the heat abstracted by cooling will be:

$$\frac{2000 \times 550}{778} - 13\, c_p\, (170 - 60) = 1080 \text{ BTU}_s/\text{sec.}$$

Allowing 10° F. temperature rise in the cooling water, we have to supply 108 lbs. of cooling water per second. The cooling is usually effected by

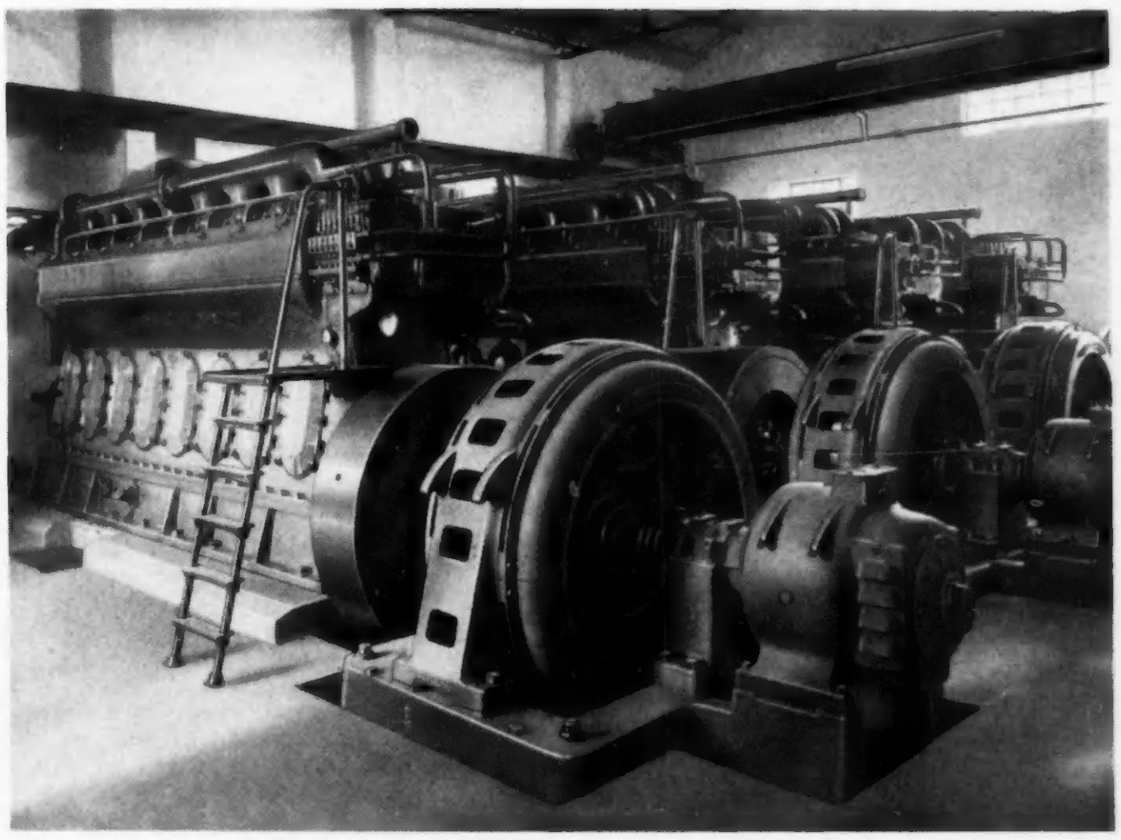
(1) cooling the casing, or
(2) by intercoolers of tubular type or
(3) by combined casing cooling and intercoolers.

With the increase of peripheral speeds in modern machines the number of stages has been reduced, each stage giving a greater pressure rise and producing more heat; to take away the heat in the surrounding part of the casing necessitates large diameter of casing and complicated castings arranged for water circulation. Cooling water not being clean as a rule, sediment is deposited quickly in the water spaces and causes reduction of the cooling effect with consequent reduction in efficiency of the machine; cleaning of the water spaces is not easy. These disadvantages of the casing cooling system are greatly minimised by the use of intercoolers. These are very effective and easily cleaned. There is another advantage in intercoolers; the air temperature at the outlet of the intercooler can be easily kept within 30° F. of the cooling water inlet temperature. In 1 lb. of saturated air at 60° F. and 30" Bar. there is .01 lb. of moisture, while in 1-lb. of saturated air at 90° F. and 70 lbs./sq. inch abs. (a condition reached frequently in the last intercooler of a turbo-compressor) there is only .006 lbs. of moisture; in other words 40% of the original moisture content actually condenses in the intercooler and can be eliminated from the air. In the usual type of casing cooled compressor the air temperature remains always above the condensation temperature, hence reduction of moisture cannot take place in such a compressor.

(To be continued).

Generating Plant for Canton Provincial Government Cotton Mills.

A comprehensive textile electrification scheme has recently been completed for the Canton Provincial Government Cotton Mills and comprises four 350 kW alternators driven by oil engines, over 160 motors ranging from 1 to 110 h.p., and 120 loom motors of about ¾ h.p., together with all the necessary switch and control gear. The illustration shows three of the four 350 kw alternators in the power station.



The Artificial Lighting of Picture Galleries.

By M. W. PEIRCE.

Illuminating Engineering Dept. of The General Electric Co. Ltd.

THERE is little doubt that the fatigue, known popularly as "Museum Headache," which often results from a visit to a public picture gallery, has as its primary cause the eye strain produced by the disturbing effect of reflections from the pictures.

The visitor to the gallery expects to be able to see and appreciate all the pictures exhibited, but the effect of reflections in glass surfaces is so common a phenomenon that he probably fails to notice the fact

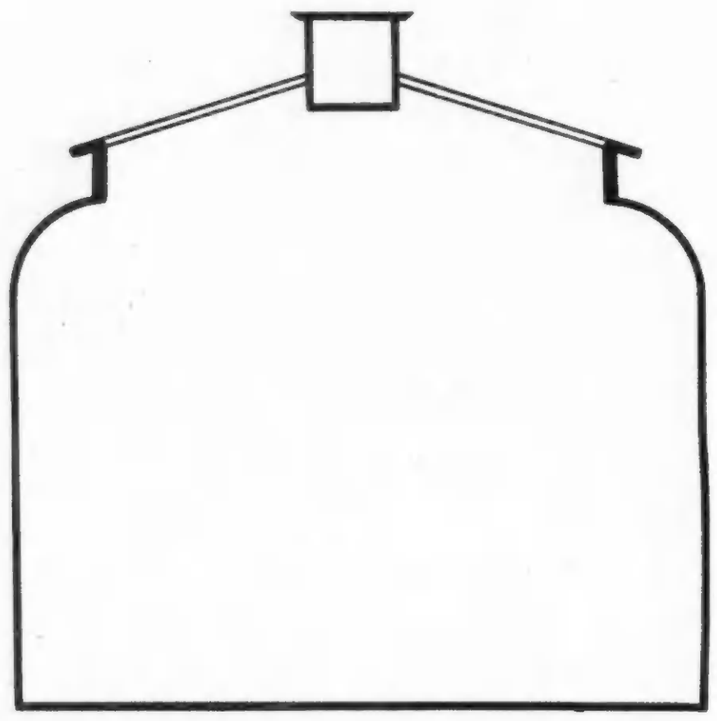


Fig. 1.—Common form of roof lighting for a double-sided gallery.

that he is constantly striving to obtain a view point in front of a picture "in order to get the best light." In consequence, the eye-strain is considerable and if it were possible to remove all the disturbing reflections which occur, the difference would be so striking that it could not fail to be noticed immediately even by the most casual visitor.

The problems involved in securing adequate lighting in picture galleries without causing unpleasant reflections have long been a matter of great interest to architects and illuminating engineers, and in 1927 there was published by the Department of Scientific and Industrial Research (D.S.I.R.) a paper giving the results of experiments carried out at their request by the National Physical Laboratory and the conclusions reached as a result of the experiments.*

Although this article deals with natural lighting, its conclusions are of the greatest importance in connection with artificial lighting as it will be clear that nearly all the basic principles which are involved in the one case apply equally to the other in so far as suitability of lighting is concerned.

The extent to which reflections in glazed surfaces of pictures prevent or hinder vision is dependent on the brightness of the reflected image in comparison with the brightness of the surface of the picture and for this reason reflections in a dark picture, *i.e.* one having a low average reflection factor, are more noticeable than the same reflections in the glazing of a picture whose average colouring is lighter. It is calculated that the average brightness of the picture must be about five times that of the reflected

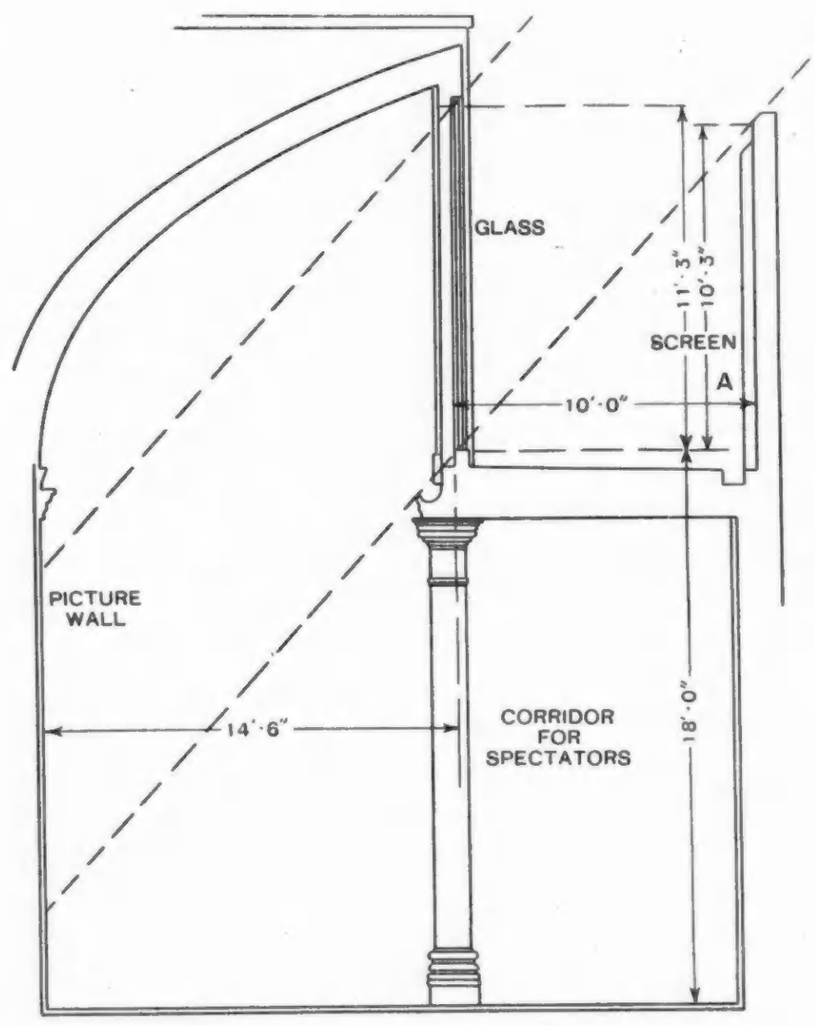


Fig. 2.—Elevation of single-sided gallery showing how the daylight lighting is directed towards the picture walls.

images if the reflections are to be considered innocuous.

The reflections which it is desirable to avoid or reduce as much as possible are caused in three ways.

1. Reflections of the source of light, whether natural or artificial.
2. Reflections of the observers and objects in the centre of the gallery.
3. Reflections of the opposite wall.

* Figs. 1, 2, 3 and 4 are reproduced from the D.S.I.R. Illumination Research Technical Paper No. 6, by permission of the Controller of H.M. Stationery Office.

With regard to 1, this can be avoided by correctly placing the light sources with respect to the picture surfaces. It is essential that all lighting should be from above and usually from an angle of at least 45° above the horizontal. The natural lighting of a picture gallery is commonly effected by means of skylights arranged to satisfy this most important requirement. In a double sided gallery where the natural lighting has been arranged in this manner it is possible to suspend artificial lighting units in the centre of the gallery and in a direct line between the skylight and the walls. It is shown in fig. 1 that the fittings can be placed so that the artificial lighting follows substantially the same direction as the natural lighting and that in both cases reflections are not normally seen by an observer.

It is essential to avoid reflections of the source of light, as otherwise it would be quite impossible to see some of the pictures.

This fact is well-recognised by all art gallery authorities. The other causes of reflections, although admittedly less important, are not so universally appreciated.

It is clear that reflections of observers and objects mentioned in 2 above, cannot be entirely eliminated and it is only possible to reduce the brightness of the reflections either by reducing the intensity of the light falling on the objects or by ensuring that the objects have a low reflection factor. Reflections of spectators can, therefore, be reduced in brightness by reducing the intensity of the lighting in the centre of the room.

The elimination of reflections of the opposite walls, and of the pictures on the walls, is more difficult

Fig. 3.—Daylight view of the single-sided gallery No. XIII. of the Tate Gallery, Millbank.

of solution as obviously the intensity cannot be reduced and the reflection factors, except of the walls, cannot be altered. All that can be done is to arrange for the walls to have approximately the same average reflection factor as the pictures so that any reflections in the glazing of pictures will be as featureless as possible. Highly polished gilt frames should be avoided as these are inevitably a cause of brilliant and objectionable reflections.

It will be of interest to examine the design for a picture gallery as recommended by the Department of Scientific and Industrial Research in their Technical Paper No. 6 (see fig. 2). It will be seen that the type of gallery recommended is single sided so that reflections of the opposite wall are minimised and that the lighting is confined to the picture wall, the spectators themselves being in comparative darkness. Single sided galleries of this type are to be found at the Tate Gallery, Millbank, and have proved extremely successful. An illustration of one of these galleries is shown in fig. 3, and perhaps the only objection that can be raised is that the lighting intensity is highest at the top of the picture wall above the pictures and falls off considerably towards the foot of the picture wall. This variation in intensity can hardly be avoided with natural lighting but with artificial lighting in the same rooms a directive effect can be introduced providing practically even lighting over the picture area.

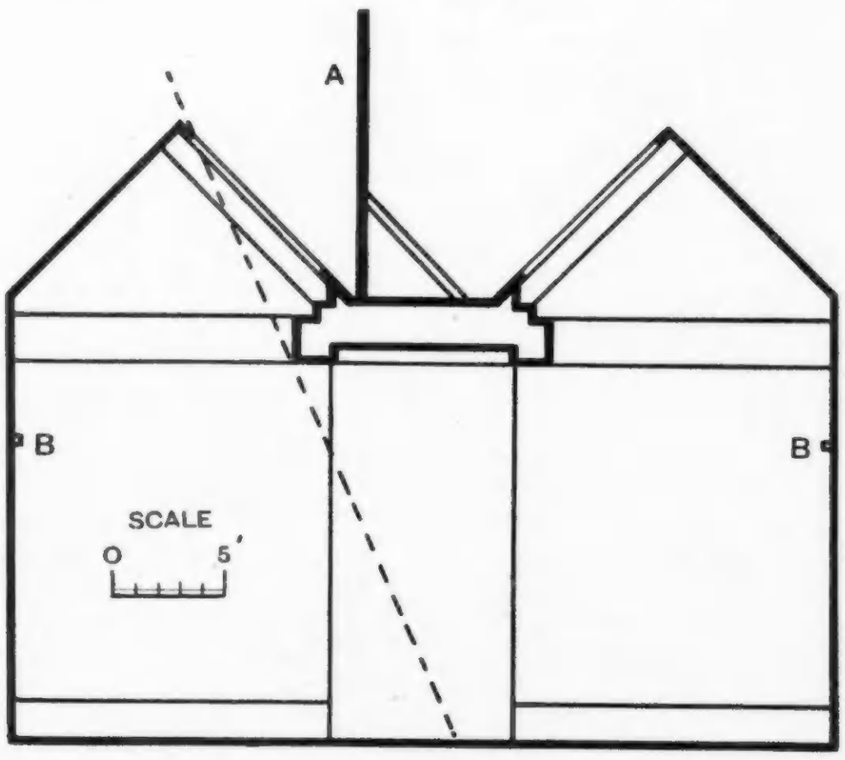


Fig. 4.—Elevation of double-sided gallery having natural lighting arranged to reduce direct light in the centre of the room.

THE NATIONAL GALLERY.

When in 1931 the artificial lighting of the National Gallery was considered by His Majesty's Office of Works the Illuminating Engineering Department of the roof might give a form of illumination following more closely the principles of lighting which have been discussed. The improvements on the daylight lighting aimed at were chiefly :—

1. A reduction of the lighting intensity in the centre of the room in order to reduce the effect of reflections of spectators themselves in the pictures.
2. A more even distribution of light on the picture wall made possible by the use of suitably designed reflectors to give the increased candle power required in the direction of the foot of the wall.

The first fittings constructed for this experimental installation, while they were not decorative in appearance, were substantially the same in principle as those which have now been installed throughout the National Gallery and the other installations illustrated and described in this article. The experimental installation is illustrated in fig. 5 and the diagrammatic arrangement of the fitting is illustrated in fig. 6. It will be of interest to compare fig. 6

Fig. 5.—Experimental installation of artificial lighting in Room XXV. of National Gallery.

The General Electric Co., Ltd., was given the opportunity of putting forward its suggestions and installing an experimental system of lighting in one of the galleries.

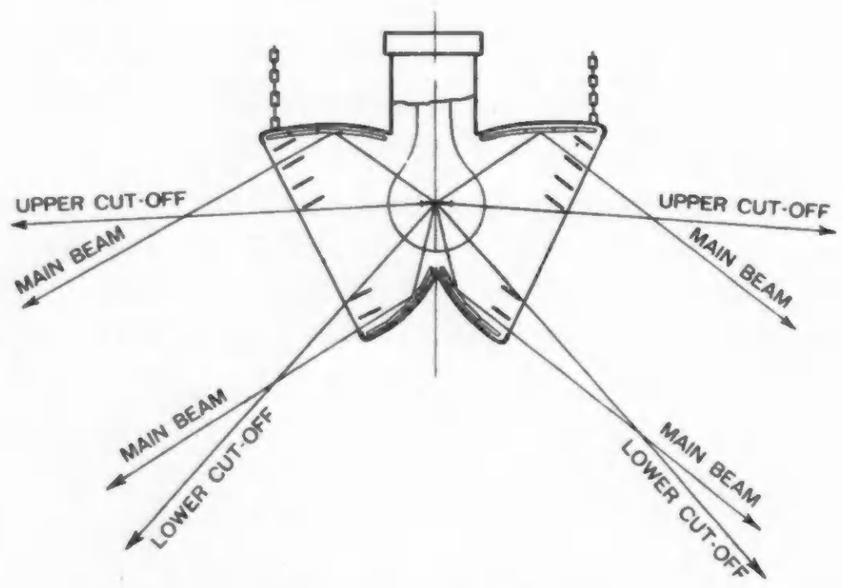


Fig. 6.—Diagram of experimental fitting at the National Gallery indicating the reflection principle employed and arrangement of louvres.

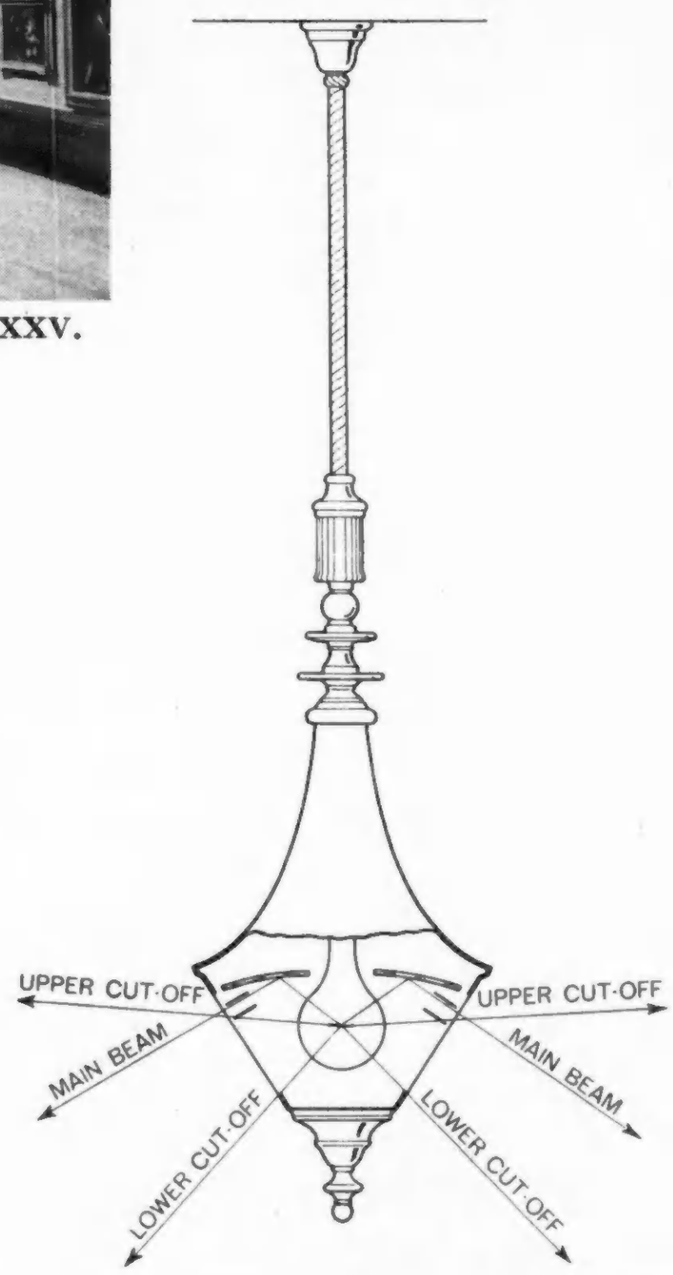


Fig. 7.—Diagram of fitting finally installed at National Gallery.

The gallery chosen for these experiments, No. XXV, has for its natural illumination large glazed panels in the roof. It would have been possible to illuminate the gallery artificially by means of reflectors over these panels, thus giving practically the same effect at night as is obtained by day. This method was considered, but it was felt that suitable fittings centrally suspended beneath the glazing of

with fig. 7 which illustrates a typical arrangement of the present-day picture gallery fitting.

Referring to fig. 6 it will be seen that the bare light from the lamp is allowed to leave the fitting only in the direction included between the two lines marked "upper" and "lower" cut-off. These two lines are drawn after the mounting height of a fitting in a particular gallery has been decided upon, and are drawn to the picture rail and the foot of the picture wall respectively. In this original fitting, reflectors were arranged both above and below the lamp.

The horizontal louvres are placed parallel to the main beam of light from the reflectors so that they offer the smallest possible obstruction to the reflected light. The contour of the reflectors is of course varied to suit the conditions in each gallery and arranged to give the correct amount of concentration towards the lower parts of the wall to ensure even lighting. The reflectors are constructed of strips of mirror glass carried on a metal backing.

The results of the first experiments at the National Gallery were extremely encouraging and the experience gained from the different arrangements which were tried out was extremely valuable. It was found, for instance, that if a small number of wide louvres was used there was a danger that horizontal shadows would be cast on the wall, while a large number of small louvres presented too much obstruction to the reflected light.

The best results were obtained with the use of lightly obscured lamps but with these lamps the "overlap" of the louvres had to be slightly increased in order to allow for the larger apparent size of the filament. The experimental installation consisted of five fittings, three of which were 2-way and the two end fittings 3-way. 1000 watt lamps were used in the first instance but it was found that the build-up of light in the centre of the gallery was such that a more even effect was obtained when 1500 watt lamps were used in the two end fittings.

SOUTHPORT ART GALLERY.

Owing to the financial crisis in 1931 it was unfortunately impossible for H.M. Office of Works to proceed with the work of the artificial lighting of the National Gallery but sufficient had been done to show

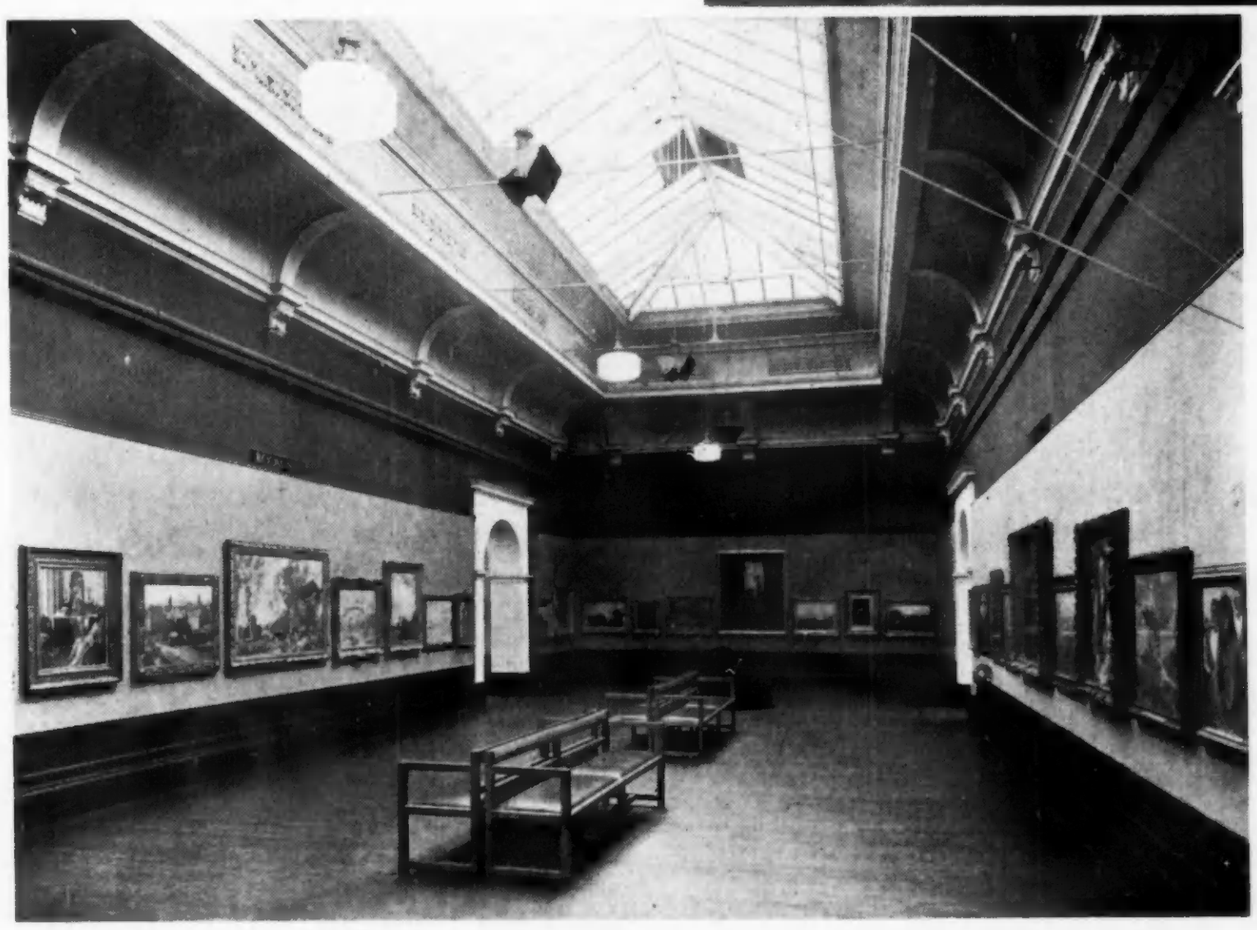


Fig. 8(b).—Daylight view of the same gallery shown in fig. 7(a).

Fig. 8(a)—Night view of the Atkinson Art Gallery, Southport, showing the artificial lighting installation.

that the method of lighting was correct in principle and to enable the G.E.C. to undertake the lighting of the Atkinson Art Gallery, Southport. This gallery consists of five rooms and the completed installation in one of these rooms is illustrated in fig. 8(a).

It is noticeable that the picture walls stand out considerably more clearly than in the daylight conditions illustrated in fig. 8(b).

The use of high wattage lamps in conjunction with concentrating reflectors directing the light on to the picture walls would result in a considerable amount of direct glare being caused to visitors entering the doorway of a gallery and to prevent this,

narrow vertical baffles were used to screen the direct light on the doorways. These baffles were arranged to be removable so that after erection of the fittings they could be cut to exactly the correct dimensions to screen the actual doorways without reducing the amount of light on the picture walls on each side of the door.

In some of the photographs reproduced these baffles may be seen to cause a shadow over the doorway. It might be thought that this shadow over the door could be removed by the use of specially shaped baffles arranged not to screen the light above a certain angle, but it must be remembered that the glare is caused by the reflected beam of light as well as by the lamp itself and it is therefore in most cases necessary to carry the baffle to the top of the fitting if the glare from the reflector is to be avoided completely. The matter is however one for experiment in each particular installation, and in some cases, such as the Birmingham Art Gallery, partial baffles have been found to give ample screening effect.

THE WALKER ART GALLERY.

The lighting of the New Extensions of the Walker Art Gallery opened by H.R.H. The Duke of Kent in 1933 was perhaps the most important of the earlier installations of Art Gallery lighting using the system which had developed from the early experiments at the National Gallery. The architect responsible for the building of the extensions was Sir Arnold Thornley.

Designs for a more decorative lantern were submitted and finally approved after modifications had been made.

The optical arrangement which had proved so successful was not altered except that the reflector beneath the lamp was dispensed with as it was considered that the reflector collected only a small amount of flux from the lamp, and it was found that its omission caused no appreciable reduction in the lighting intensity obtained on the wall. The omission of this reflector allowed the lower set of louvres to be replaced by a horizontal strip of metal, thus producing a more sharply defined cut off at the foot of the picture walls. The revised diagrammatic arrangement is shown in fig. 9 which also illustrates a further innovation introduced at the request of the architect, namely a pilot light operated by a separate circuit which can be used by the night watchman at times when a small amount of light is required in the gallery. Special square moulded glasses were made for this purpose and incorporated in the bottom of the fittings and these can be illuminated by a 60w. or 100w. pilot lamp when the main lighting is not required.

It is worthy of note that the system of lighting is extremely economical both so far as the number of fittings and total wattage is concerned. At the extensions to the Walker Gallery a total number of only eighteen fittings were required for the illumination of four separate rooms, having in all a wall area of approximately 12,000 square feet. It is not however, always possible to use a centrally suspended line of fittings owing either to the design of the roof, wiring difficulties, or architectural considerations and the Bridge Gallery illustrated in fig. 10 is a case in point. Here six fittings were used for the lighting of a wall of approximately 600 square feet, the increased number of fittings being required first because a separate line of fittings is used for each wall and secondly, because the closer projection of the fittings from the wall necessitates their being closer together.

Fig. 10.—Artificial lighting of the Bridge Gallery, Walker Art Gallery.

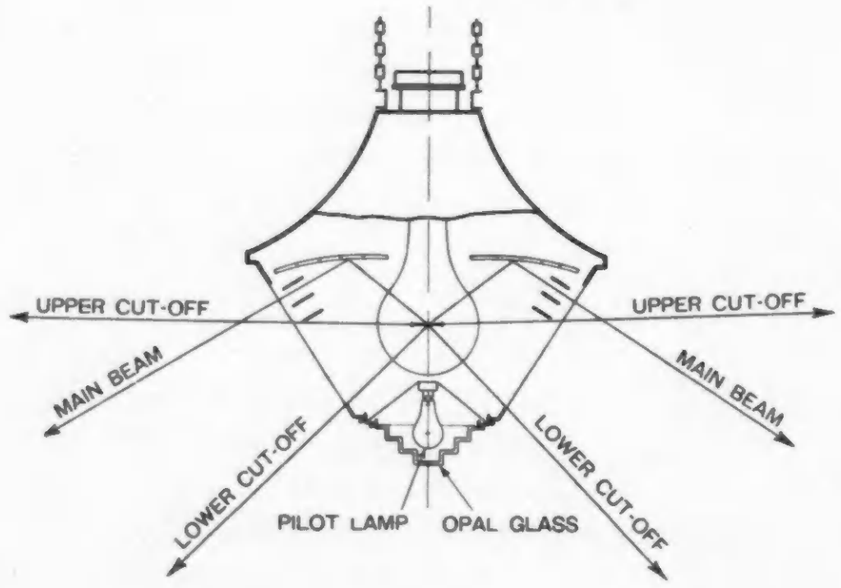


Fig. 9.—Diagram showing arrangement of fitting used in the Walker Art Gallery, New Section.

Fig. 11.—Gallery No. 6, Walker Art Gallery. This gallery is of the "Embayment" type.

It will be seen however, that as in the case of the old section of the Walker Gallery which is described in a later paragraph, the very desirable feature of a comparatively dark central area in the gallery is retained as is also the necessary oblique angle of the lighting: moreover, as may be seen from the photograph, this particular room is not suitable for lighting by means of a central line of fittings.

Another room in the new section of the Walker Art Gallery, in which a system of centrally suspended fittings is unsuitable is illustrated in fig. 11. This is known as the Embayment Gallery and is of a similar type to the Duveen Gallery at the National Gallery. The natural lighting is provided by means of separate laylights over each embayment and the lighting in the centre of the room can be controlled as desired. It will be appreciated that this form of natural lighting aims at reducing the intensity in the centre of the room occupied by spectators. In this type of gallery the artificial lighting is best carried out by means of a series of reflectors concealed above each embayment, either above the panels of the laylights or behind a suitable beam as in the case illustrated.

The question of lighting the old section of the Walker Art Gallery which was re-decorated and opened at the same time as the new extensions, presented a number of new problems as it was found that it would be extremely difficult to wire the rooms for centrally suspended fittings. It was decided therefore to suspend fittings comparatively close to the walls although it was realised that a considerably larger number of units would be required. One of the difficulties under the new conditions was the adequate lighting of the end walls of the rooms and particularly the corner positions. The type of fitting used for the Bridge Gallery (fig. 10) was used for the more straightforward positions, but for the corner positions in these larger galleries it was necessary to design a fitting which would give the same effect as two units arranged at right angles to one another.

The method finally decided upon was to use a square fitting with two of its sides completely blanked off, the arrangement being in fact a small edition of the normal 2-way picture gallery fitting, except that the blanks were fixed in two adjacent sides instead of two opposite sides with the reflector system arranged accordingly.

Fig. 12.—One of the galleries of the new extensions at the Walker Art Gallery. The glass pilot lights incorporated with the fittings can be seen but are not switched on.

From the technical point of view the lighting effect obtained was as satisfactory as with the use of the central fittings, the chief objections being the increased number of fittings and wiring points and the increased total wattage to produce the same lighting effect.

THE ASHMOLEAN MUSEUM.

The lighting of the picture gallery of this famous museum was completed in 1933, the fittings being of the type used for the New Section of the Walker Art Gallery except that the pilot lighting was not in this case required by the architect and a suitable ornament was used to replace the special glass dish.

THE BIRMINGHAM ART GALLERY.

In reviewing the details of design before manu-

facturing the fittings for this important installation, it was decided to experiment with the use of bent mirror glass sections as an alternative to the mirror glass strips which had hitherto been used. One of the advantages of employing bent glass was that the glass blanks could be bent to the exact curve required for a particular fitting, cut to size and finally silvered and protected with copper backing, the resulting reflector being of a more durable nature than the strip reflectors previously used which were cut to size from sheet mirror glass.

Fig. 13.—Room No. X, Birmingham Art Gallery. The successful lighting of the angled corners of this room should be noted.

A further and more important advantage of the new type of mirror was that the light could be controlled more accurately since the continuous curve of the reflector could be made to follow the designed curve exactly. A separate reflector was of course used for each operating side of the fitting, that is to say, a two-way fitting would be equipped with two single piece bent mirrors and a three-way fitting with three mirrors.

It was hoped that a mirror of standard shape and size might be made which could be adjusted in the fitting to give the necessary variation in beam angle and distribution to suit different situations but it was found the requirements in different instances were not sufficiently similar to permit even this amount of standardisation. The experiments with the bent reflectors were however successful and they were therefore used for the whole of this installation.

A point needing special attention at the Birmingham Galleries was the fact that some of the smaller rooms while not being quite square were not sufficiently rectangular to permit the use of two fittings, and it was agreed that they could best be lighted by means of a single 4-way fitting. The standard fitting, however, which is square in plan would not be quite suitable as the line drawn through the filament of the lamp and the diagonals of the fitting would not reach the corners of the room and correct lighting in the corners would not be obtained. To overcome the difficulty rectangular fittings were constructed having their sides proportional to the dimensions of the room for which they were intended. The reflector and louvre systems in these instances were of course complicated by the fact that two sets of angles had to be calculated for and incorporated in the one fitting.

In determining the mounting height for the fittings, it is necessary to work to the longer cross section of the rooms in order to ensure that there shall not be reflections of the fittings in the pictures hung on the end walls. This results in a mounting height which is somewhat higher than is normal with respect to the two side walls of the room.

In the installation at the Birmingham Gallery (fig. 13) the square opal glass was incorporated in the

Fig. 14.—Royal Institute Gallery, Piccadilly.

fitting as at the Walker Gallery, but in this case there is no separate pilot lamp and the glass is illuminated continuously. This arrangement, since it gives a certain amount of direct lighting in the centre of the room, is not strictly desirable, but it was used in this case at the special request of the authorities as the rooms are sometimes used for assembly purposes and some additional lighting in the centre of the room was required.

ROYAL INSTITUTE GALLERIES, PICCADILLY.

These rooms are used for exhibition purposes by the Royal Society of Portrait Painters, The Pastel

Fig. 15.—View of room No. X, National Gallery. A small amount of indirect lighting has been introduced at the special request of the authorities.

Society, Photographic Societies and other similar bodies; also for evening functions, such as public dinners and dances. It had to be pointed out at the outset that the lighting requirements for the two purposes were from many points of view diametrically opposed and it was eventually decided to retain the then existing general lighting fittings and in addition to install picture lighting fittings for use during the various exhibitions.

The arrangement of the fittings in the large room was a departure from that of centrally suspended fittings, which is customarily used, owing to the unusually great width of the gallery. Four fittings were used for the lighting of one end of the room and each was equipped with a 1000w. lamp. A single 3-way fitting suspended in the centre of this area at a higher mounting height could have been arranged to give practically the same distribution, but a single 1500w. lamp, which is the largest size of lamp which could have been employed, would not have been sufficiently powerful.

Fig. 16.—Entrance to the Venetian Room, National Gallery.

Another of the rooms of these galleries is illustrated in fig. 14. This photograph was taken during the exhibition of the Royal Society of Portrait Painters, the picture lighting fittings only being used. It was impossible to avoid casting shadows of the crystal pendant fittings on the walls, but the height of these general lighting fittings was carefully adjusted so that the shadows did not fall into the picture area.

THE NATIONAL GALLERY.

In 1934 nearly three years after the original experiments, H.M. Office of Works was finally able to proceed with the lighting of the whole of the National Gallery. The experiments with the original picture lighting fittings had been sufficiently successful for the members of the National Art Galleries committee, of which the First Commissioner of Works is chairman, to decide that the lighting should be carried out on a scheme based on the suggestions which had been put forward by the G.E.C. The experience gained during these experiments, and subsequently in carrying out the installations described above, was of the very greatest assistance in the many new problems which arose when the time came to consider every detail of the system as applied to each particular room.

The first step was to decide upon the number of fittings to be installed in each room and the exact position of each fitting. It had been decided that fittings square in plan and uniform in design should be used throughout the Gallery and this being the case positions would normally be chosen so that the 3-way fittings at each end of the rooms were equidistant from the end and side walls. This is necessary if the corners of the fittings are to be correctly in line with the corners of the room. In some of the rooms it was found impossible owing to the arrangement of the roof trusses to suspend the fittings in the desired positions and they had to be fixed in some cases nearer and in other cases further away from the end wall. In previous installations difficulties of this sort had been overcome by the use of rectangular fittings, but as mentioned above, the use of the standard square design throughout the gallery was desired and some other solution had to be found. Eventually, the problem was solved by carefully adjusting the position of the lamp in the fitting according to the location of the latter with respect to the end and side walls, and by arranging the reflector system to give the necessary variation in distribution in order properly to illuminate both the end and side walls.

Fig. 18.—One of the fittings installed in the National Gallery.

Although square fittings of uniform design were used throughout the gallery it was thought that the actual size of the fittings should in some cases be varied as the rooms themselves vary considerably in size and it was necessary that the fittings should be correctly proportioned according to the rooms in which they were to be used. Actually three different sizes are employed having sides of 23 ins., 21ins. and 19ins. respectively. The reflectors and louvre systems are removable and interchangeable in each size of fitting, so that once the positions had been decided upon the exterior housings could be erected and wired up ready for the fitting of the correct reflectors and louvres.

Fig. 17.—Close up of a corner of a room at the National Gallery under artificial lighting.

It is of interest to mention that in Gallery No. 1 in addition to the picture lighting units it was decided to instal a system of indirect lighting on to the ceiling, thus giving additional general lighting particularly in the centre of the room. It is in this room that important guests are formally received and it was naturally desirable that a good general intensity should be provided as a contrast to the remaining rooms which are purposely arranged to be comparatively dark in the centre.

TATE GALLERY.

The lighting equipment now being installed in the Tate Gallery is carried out by means of fittings exactly similar to those described for the National Gallery. There are a total number of 16 rooms in which the artificial lighting is being installed and 40 fittings will be used each being of the large size.

Most of the rooms at this gallery are similar in elevation and the reflector systems and mounting heights of fittings are consequently more uniform than in the case of the National Gallery. There are, however, rooms in which it has been necessary to mount the fittings closer to the end walls than to the side walls, where an arrangement has been adopted similar to that used at the National Gallery.

DESIGN CONSIDERATIONS.

From the foregoing descriptions of installations using the basic principles of the lighting fitting

originally designed for the experiments at the National Gallery it will be evident that the system is applicable to many art galleries and that where applicable it provides by far the most economical and satisfactory method of lighting. At the same time it must be

Fig. 19.—Final installation in Room No. XXV, National Gallery. The original experiments were carried out in this room (see fig. 5).

appreciated that while the basic principles remain the same yet the details must be calculated separately for each individual unit in each installation. It is possible in most cases to use a standard exterior housing throughout a particular gallery but it is not possible to standardise in any way the arrangement of the interior reflectors and louvres.

The procedure which must be followed before the fittings for any room of a particular gallery can be put in hand, are briefly as follows :—

1. Plans and cross sections of the rooms are obtained and carefully checked for accuracy, as quite small errors in the measurements may result in the calculated beam angles being considerably at fault. Particular care must be taken to note the positions of the features of the ceiling as these will have a bearing on the positions to be chosen for the fittings.
2. The mounting height for the fittings is chosen and must be not less than a certain minimum, governed by consideration of reflections of the fittings in the picture surfaces. The height finally selected is somewhat in excess of this minimum as the surface of an oil painting is never smooth and the irregularities result in a fairly wide dispersion of the reflected rays which it is desired to keep from the eyes of spectators.

It is not in all cases possible to avoid reflections in the upper parts of the larger pictures if the observer is standing close to the wall, and it is usually assumed that the observer would move away from the picture to view the upper parts rather than stand his ground and look upwards at an increased angle. The reflections from the topmost parts of large pictures can be avoided by choosing positions for them on the walls not directly opposite the lighting fittings ; this arrangement results in the reflected rays passing to one side of an observer standing in front of the picture.

3. The number and type of fittings and their fixing positions can now be decided upon. In a rectangular gallery suitable for a central line of fittings two three-way fittings are used for the end positions each of which illuminates one end wall and part of each side wall. The best position for these end fittings is such that they are equidistant from the end and side walls, but small variations can be allowed for in designing the reflectors if architectural considerations, such as the position of beams in the ceiling, make this necessary.

If the length of the gallery is more than twice the width then a third fitting must be used and in some

Fig. 20.—Sheffield Art Gallery showing artificial lighting by means of trough reflector.

cases two or three additional fittings are required. It is clear that the centre fittings must not be allowed to illuminate the end walls, as the angle of lighting from these would be such as to cause reflections.

These central fittings are therefore of the two-way type with two opposite sides blanked.

It is sometimes convenient to introduce a rectangular fitting either to reduce the total number of fittings in a room or in order to utilise convenient fixing positions which could not otherwise be

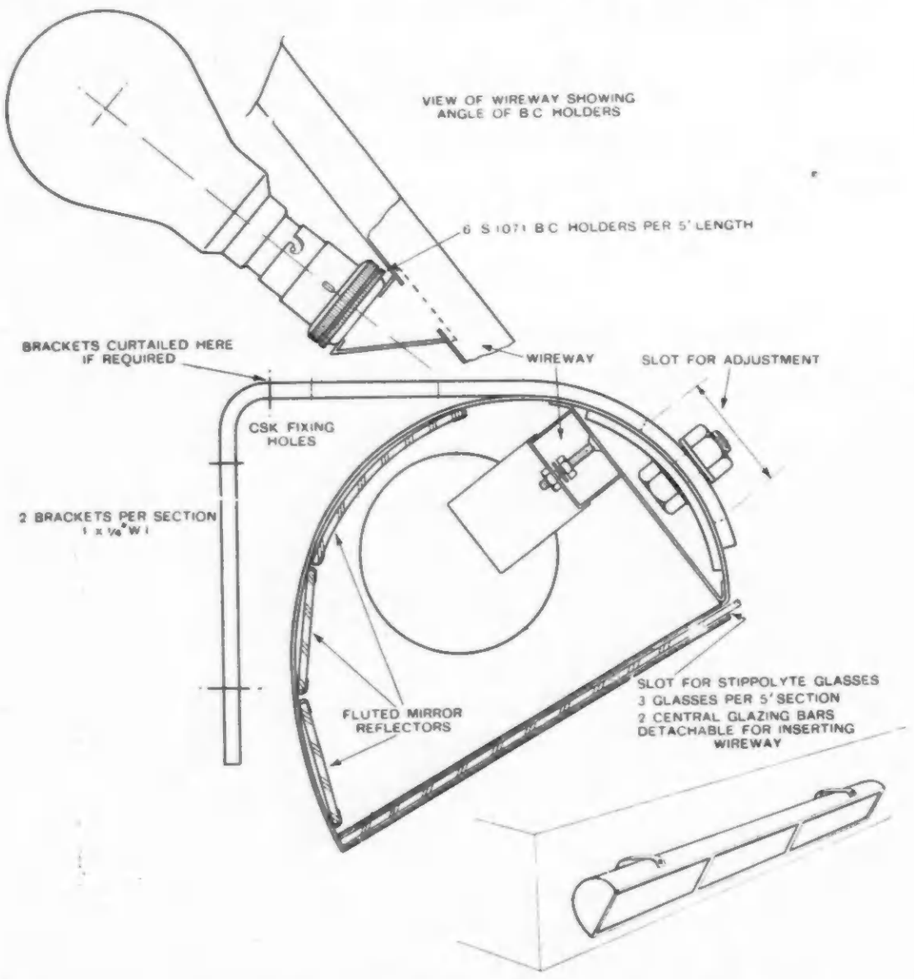

VIEW OF WIREWAY SHOWING ANGLE OF B.C. HOLDERS
6 S.1071 B.C. HOLDERS PER 5' LENGTH
BRACKETS CURTAILED HERE IF REQUIRED
WIREWAY
SLOT FOR ADJUSTMENT
CSK FIXING HOLES
2 BRACKETS PER SECTION
1 x 1/16" W.I.
FLUTED MIRROR REFLECTORS
SLOT FOR STIPPOLYTE GLASSES
3 GLASSES PER 5' SECTION
2 CENTRAL GLAZING BARS DETACHABLE FOR INSERTING WIREWAY

Fig. 21.—Typical trough reflector for picture lighting.

considered. This is not of course possible if the exterior design of the fittings is to be uniform throughout.

4. The size of lamp to be used in each fitting is now chosen to give a satisfactory intensity on the vertical surfaces. In cases where there are three or more fittings it is sometimes desirable to use a smaller size lamp in the centre fittings, as there may be considerable build up of intensity if the fittings are spaced comparatively close together.

It has been found that an intensity of 5 foot-candles on the vertical surfaces of the walls is in general satisfactory, and this figure may be taken as an average for the installations described. Higher intensities have been found to cause increased cross reflections in the galleries, and are not to be recommended. If, however, there is any direct lighting in the centre of the room, it is desirable to increase the intensity on the walls in order to retain an adequate contrast.

5. The contour of the reflector and its position with respect to the lamp filament is next calculated. The design of reflector contours to provide a given calculated distribution is a somewhat lengthy process and it is not therefore proposed to go into the question in detail in this article. It may be mentioned however, that a method of design has been fully described.*

* "The Theory and Design of Illuminating Engineering Equipment," by L. B. W. Jolley, J. M. Waldram and G. H. Wilson (Chapman and Hall).

6. Finally the limiting angles for the louvre system are set out and the number, size and position of the louvres decided upon.

ALTERNATIVE METHODS OF ARTIFICIAL LIGHTING.

As mentioned already the National Gallery system is not universally applicable to Art Galleries and in some cases such as the Embayment Gallery at the Walker Art Gallery alternative methods are employed.

In galleries of the type recommended by the Department of Scientific Industrial Research, fig. 2, which are arranged so that the natural lighting in the centre of the room is reduced in intensity, the artificial lighting can usually be concealed behind the beam at the lower edge of the glazing providing the daylight lighting. Fig. 20 is an illustration of the artificial lighting at Sheffield Art Gallery which is carried out by means of a trough reflector carried behind a beam in this manner

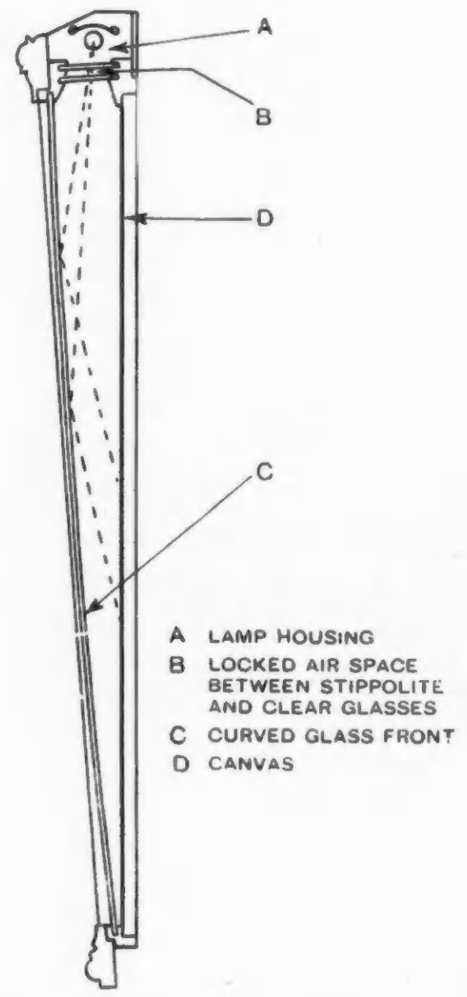


Fig. 22.—Diagram showing the principle of K-ray illumination for individual pictures.

The position of the trough reflector is arranged so that reflections are not visible in the pictures and the contour of the reflector is designed to give an even distribution of light down the picture surface. Upper and lower cutoff angles are provided so that the picture wall only is illuminated and the desirable low general intensity in the room is retained.

In galleries of this type the natural lighting is usually only fully effective on the side walls and the end walls therefore are frequently not hung. It is

possible, however, to carry the artificial lighting reflector across the ends of the galleries if it is desired to use these walls for the exhibition of pictures.

In general it may be said that the method is fully as effective as the use of central fittings though it is admittedly more expensive both in first cost and running costs, owing to the large number of small lamps used. It should also be mentioned that as the smaller lamps are rated at a lower efficiency, the light has a greater proportion of red in its spectrum and that the colour rendering of the pictures may therefore be altered to a small extent.

LIGHTING OF INDIVIDUAL PICTURES.

A problem quite distinct from the lighting of an art gallery but nevertheless one which is of considerable importance is the individual lighting of separate pictures. In private houses it is often desirable to provide additional lighting for a small number of separate pictures rather than general lighting of a wall on which a number of pictures are hung.

As will be clear from the theoretical considerations already discussed, the normal room of a private house is not really suitable for showing pictures as the natural lighting is usually provided by windows at approximately the same level as the pictures and the fixing positions of artificial lighting fittings are also, in most cases, likely to give rise to reflections in the picture surfaces.

The positions for pictures should obviously be chosen carefully so that these reflections are least noticeable and if local lighting is correctly applied the problems can usually be satisfactorily solved. The object aimed at is to increase illumination on the picture so that the effect of the reflections is as far as possible overcome, and it is very desirable to confine the additional illumination to the picture itself as this undoubtedly gives it an added attractiveness.

The most common form of local lighting for a picture is the familiar bracket fitting carried either from the picture frame or from the wall just above the picture and using one or more line filament lamps according to the length of the picture, housed in a suitable reflector fitting. One of the limitations of this method is that it is not possible to design a reflector housing of small dimensions to give very even lighting of a large picture and while by critical adjustment a fairly satisfactory effect can be obtained with a medium sized picture, the adjustment is easily lost and the lighting too often becomes a mere patch at the top of the picture.

Fig. 23.—Illustrations of a picture (left) illuminated by means of a projecting lighting fitting and (right) with K-ray illumination.

A form of trough reflector which is more satisfactory from the lighting point of view is illustrated in fig. 21 and, as will be seen, a comparatively large reflecting area is used in conjunction with general service gasfilled lamps. This arrangement is considerably more efficient and can be used effectively with large or small pictures. The reflector is large enough to be provided with screening louvres to cut off the light at the level of the top of the picture after the position of the reflector itself has been adjusted. In design, the reflector is similar to that used for the installation illustrated in fig. 20, though when used for lighting individual pictures, separate

short lengths are employed which are just sufficient to give the necessary cover.

The objection to any form of trough reflector mounted comparatively close to a picture is that it is very conspicuous even though it is correctly placed so that its reflections are not seen by the observer. In the lighting installations for large galleries where the special centrally suspended fittings have been used it is particularly remarkable that the visitor on entering a room has his attention attracted to the brightly illuminated vertical surfaces of the picture

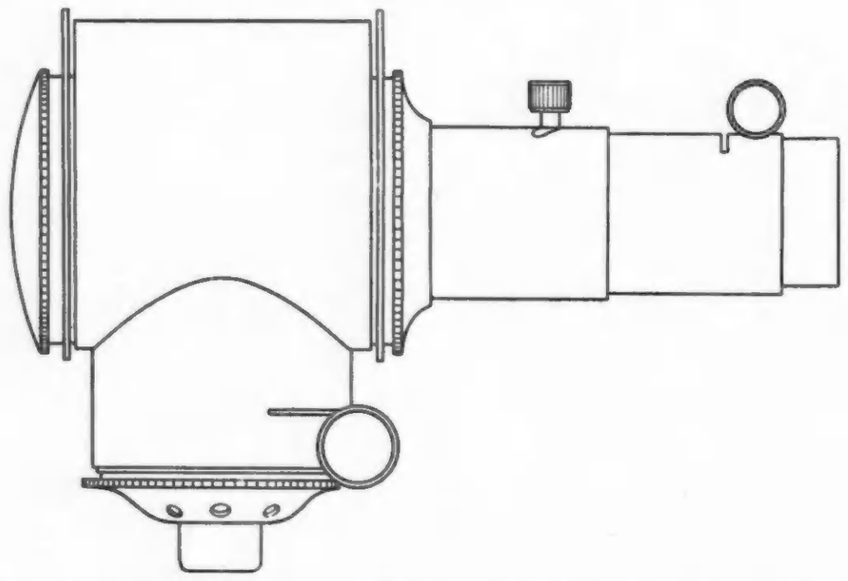


Fig. 24.—Diagram showing arrangement of Midget Spotlight for picture lighting.

walls and unless he definitely looks for the lighting fittings he is not conscious of their presence. The effectiveness of any picture lighting installation is greatly enhanced by this feature and the two interesting methods of individual picture lighting described below both give this very desirable effect.

THE K-RAY (PATENT) SYSTEM.

In this system the partial reflection from glass surfaces is actually made use of by constructing the frame of each picture so that there is sufficient room to conceal lamps at the top of the picture behind the glazing. The glass is usually curved slightly as shown in fig. 22 and has the effect of reflecting light from the lamps onto the picture. The percentage of light reflected by a glass surface increases very rapidly as the angle of the ray striking the glass becomes more oblique and the direct rays falling on the glass near the foot of the picture are almost totally reflected. The amount of light reflected off the glass onto the picture gradually increases from a minimum at the top of the picture near the lamps to a maximum at the bottom where the intensity would otherwise fall considerably. The intensity over the whole picture is therefore very even, while the illumination is confined to the picture itself, being, in fact, trapped between the glass and the picture surface. Since the lamps are effectively concealed above the picture there is no apparent source of illumination and the observer is, therefore, not distracted in any way. If it is desired to attract particular attention to the pictures, the general lighting in the room should not be too great, but even in a room brightly lit by daylight, this type of artificial lighting can be used and will to a certain extent overcome the very bright reflections caused by the windows.

MIDGET SPOTLIGHTS.

An alternative system of lighting pictures individually is by the use of special spotlights (fig. 24). These spotlights are constructed on the principle of a magic lantern and consist of a small low voltage projector lamp, spherical reflector, and condenser and objective lenses. A very concentrated beam of light is produced the divergence of which can be varied at will. The projectors are so small that they can be concealed behind a curtain or alternatively they can be made to project a beam of light through a small hole of about one inch diameter in the panelling of a room.

In use a suitable position is chosen for the projector, probably opposite to the picture to be lighted and the divergence of the circular beam adjusted so that the picture is fully covered. A screen is then introduced in the projector and cut to minute accuracy so that the spot of light projected onto the wall fits the picture exactly and does not overlap the frame at any point.

The screen introduced may of course be cut to any shape so as to illuminate say an oval picture or any object in the room. In the latter case since the shape of the beam is arranged to fit the object to be illuminated exactly, there is of course no shadow of any sort on the wall behind the object.

The lamps used with these miniature projections consume 48 watts at 12 volts and the total amount of light from each is, therefore, limited. They are extremely effective however even in a comparatively brightly lighted room, owing to the fact that the light source is invisible and the additional light is confined exactly to the picture. The projectors can easily be concealed although their position may be betrayed in a smoky atmosphere in which the concentrated beams can be seen. It should be mentioned that the low voltage projector lamps run at a very high efficiency and consequently the light is particularly white in character, that is to say, there is a greater percentage of blue light than in the high voltage lamps of small wattage.

A point of particular interest in regard to these small projectors is that they can usually be used quite successfully when fixed in positions which would be unsatisfactory for any of the other types of lighting fitting discussed, that is to say, in positions which would normally cause serious reflections. It is necessary however to emphasise in this case that the pictures must not be glazed as the reflections in the glazing would be objectionable.

Generation, Distribution and Use of Electricity on Board Ship.*

PART II.—ELECTRIC PROPULSION.

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CHOICE OF SYSTEM.

Present-day practice has resolved the variety of schemes which have been put forward for electric ship propulsion during the past 25 years into two classes, namely (1) turbo-alternators with synchronous motors, for large ships; and (2) Diesel engines with d.c. generators and motors, for small ships. The line of demarcation between these two categories is not very clear. The maximum horse-power permissible with direct current is limited by the current to be carried by the commutators, control gear, and cables.

On the other hand, at this limit, the maximum economical limit of the Diesel engines has not been reached. An attempt to bridge over the gap between the two methods is the suggestion to use Diesel engines with a.c. generators, and synchronous motors. This has not yet been put into practice, but may have possibilities in the future.

TURBO-ELECTRIC DRIVE.

For very large ships there is little doubt that the turbo-electric drive is the most suitable at present.

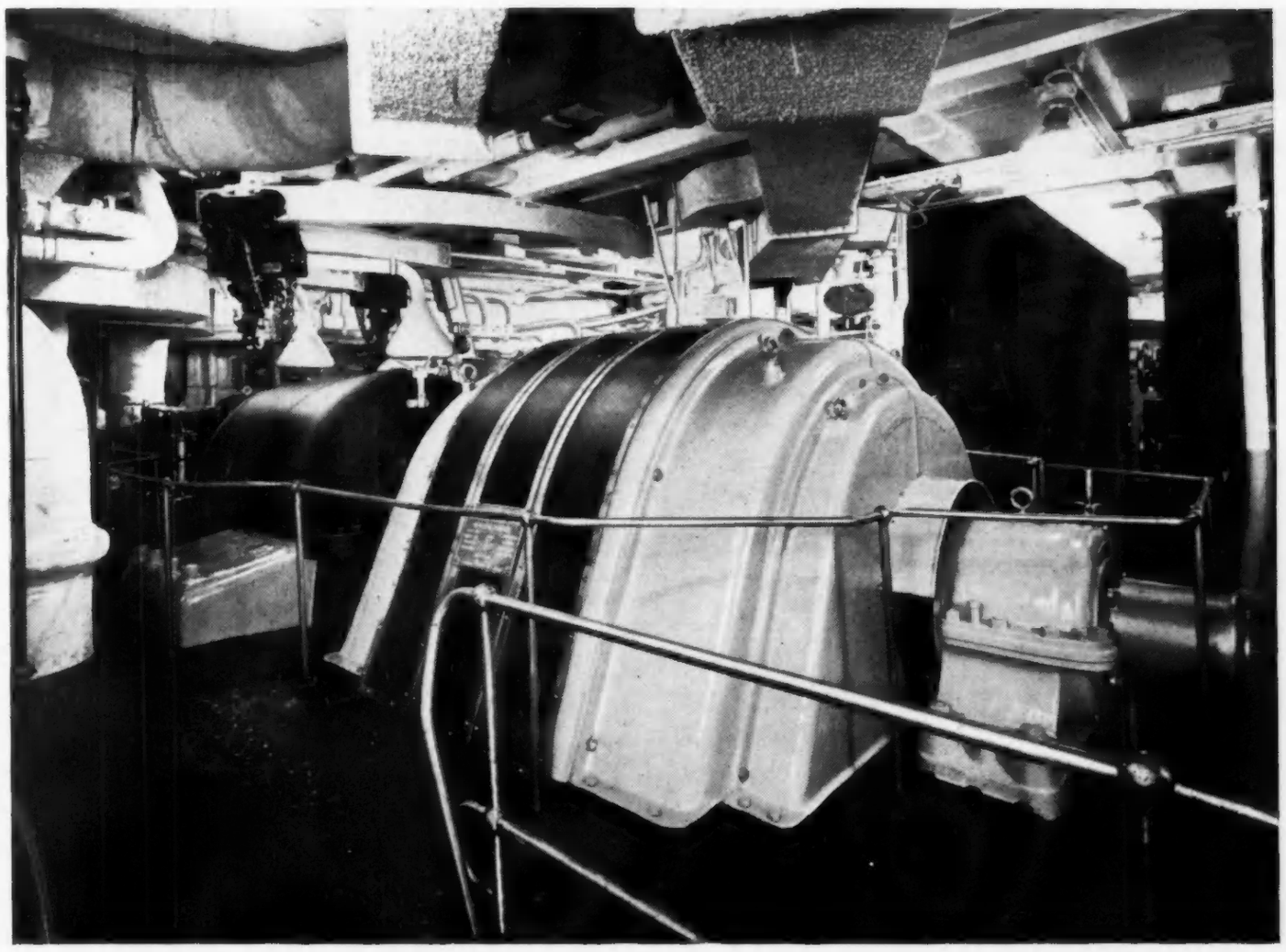

Fig. 12.—One of the two 7,500 kW, 3,300 volt, 3 phase turbo-alternators installed in the "Queen of Bermuda."

With this scheme, the a.c. generators are direct-coupled to turbines and supply 3-phase current to synchronous propulsion motors.

The frequency at normal speed has been usually fixed at 50 cycles per sec. for ships built in this country, probably because it is the standardized frequency for land practice. Actually there is no reason why the frequency should not be chosen at

* Paper read before the Institution of Electrical Engineers. 22nd Nov. 1934.

any value, having regard to the speed of the turbines and alternators and to the windings of the alternators and motors. In the French ship "Normandie," the

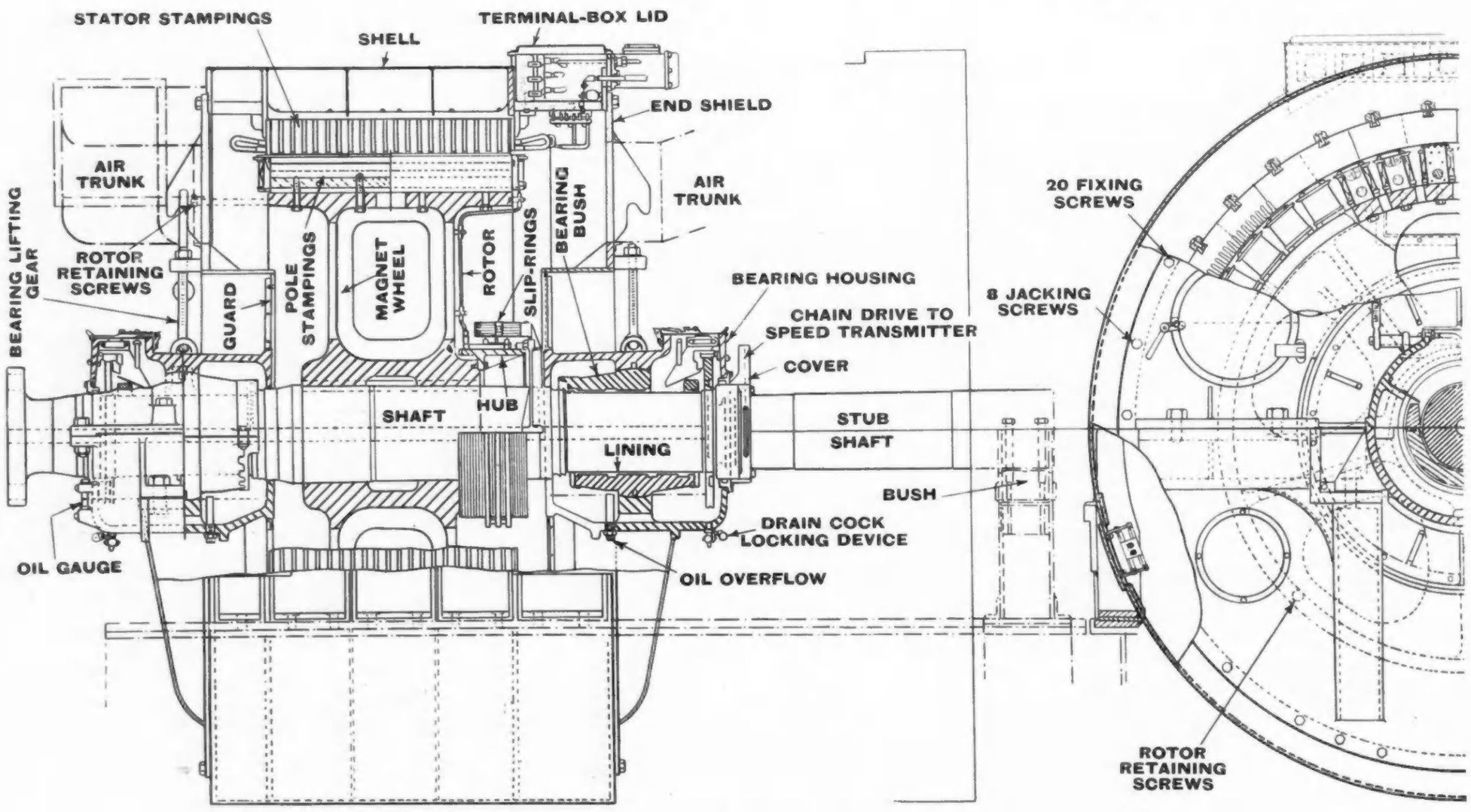

Fig. 13.—Sectional arrangement of 3,000-volt 5,000 s.h.p. ship propulsion motor.

frequency will be 81 cycles per sec., the alternators running at 2,430 r.p.m.

Turbo-Alternator Design.

The electrical design of the alternators (fig. 12), is little different from that common in land practice the chief point being that all insulation must be of special quality for use in a damp salt-laden atmosphere with larger variations in temperature. The mechanical design of the turbine and alternator rotors, however, presents points of interest, since there must be no critical speed below the normal speed of rotation. Care must also be taken of the stresses occasioned by rapid deceleration when reversing the propellers.

The alternator is usually ventilated by means of a closed air-circuit, the air being cooled by sea water. Heaters are placed in the air-circuit to avoid extreme variations in temperature when the machine is standing.

Since there is no relation between the positions of the turbine shaft and the propeller shaft, as there is in a geared turbine drive, a very compact lay-out is possible. The condenser is placed immediately below the turbine, and the cooler below the alternator.

The relative merits of the induction motor and the synchronous motor for ship propulsion have frequently been discussed elsewhere. The principal reason for the choice of the synchronous motor lies in the higher power factor, which reduces the size of the alternator, cables, and switchgear.

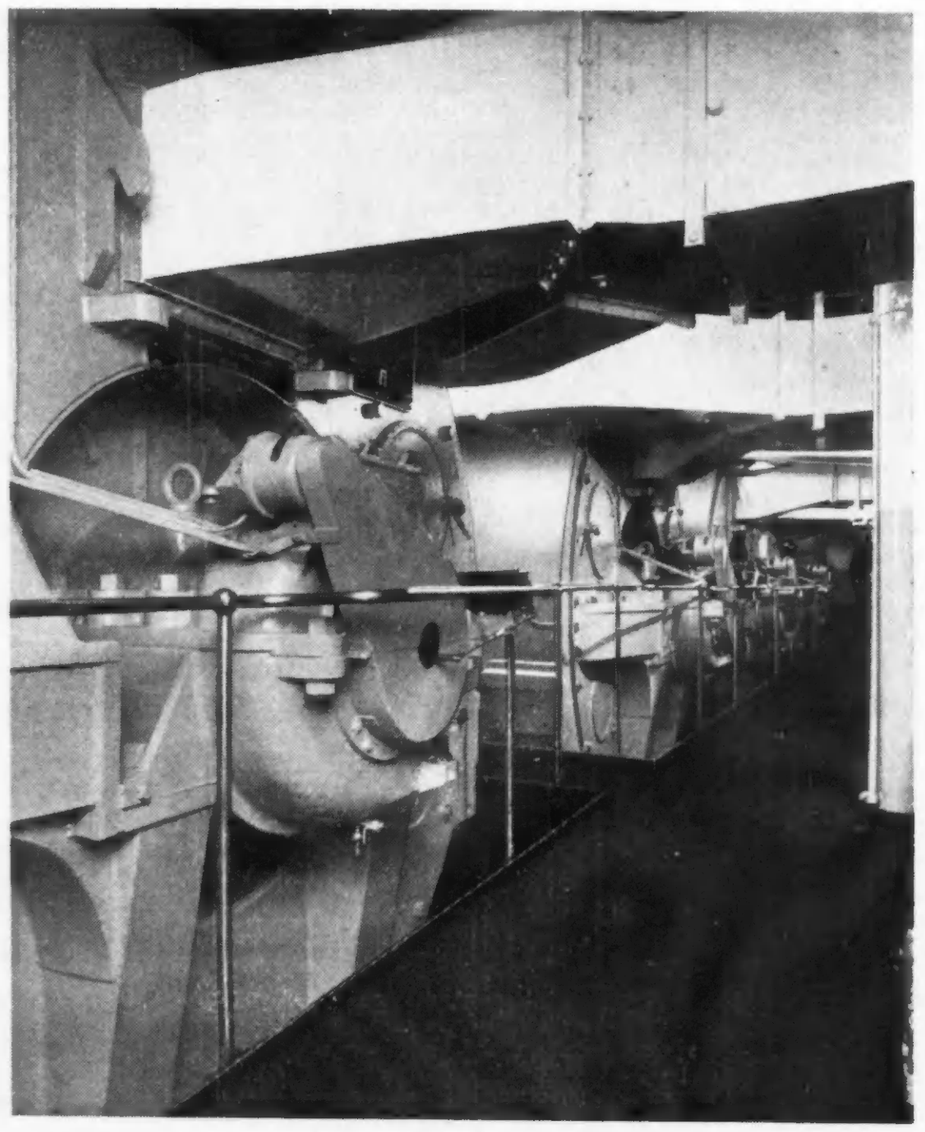

Fig. 14.—Four 4,750-s.h.p. propulsion motors, showing disc-lubricated bearings and ventilating trunking. The small generators on bearings are for operating speed indicators.

Motor Design.

The electrical design of the motors (fig. 13) again follows land practice, except for the insulation. Care must be taken in the design of the pole-face damping winding which is used for starting and reversing. This winding is not so efficient as a complete squirrel cage owing to the interpolar gaps, but it can be designed to give sufficient torque for rapid reversals.

Ventilation of the motors is effected by separate motor-driven fans through a closed circuit, or the air may be passed through coolers back into the motor room. Heaters are placed in the air-circuit to avoid extreme variations of temperature when the machines are standing.

The mechanical design of the motors is characterized by the fact that every part must be as rigid as possible and yet no weight must be wasted. Considerable ingenuity has to be exercised to fit the motors into the space available, having regard to accessibility for inspection and repair. The lubrication of the bearings has to be fully effective down to very low speeds. This problem has been solved by the use of disc and scraper lubrication (fig. 13).

In twin-screw ships, two alternators are provided, and for full speed each alternator supplies current to one motor. For cruising speeds it can easily be arranged that both motors are supplied from one alternator, with a consequent increase in efficiency.

Operation.

In a twin-screw ship, when running normally with two alternators and two motors, there is no question of the alternators or motors being overloaded except when the ship is being turned. Under the condition of full helm the alternator and motor on the inboard side of the circle tend to take more load, but they are prevented from doing so since the steam admission is limited to that required for full load. The alternator and motor on the outboard side of the circle will take a reduced load. When, however, both motors are driven from one alternator, they are capable of absorbing twice the power of the

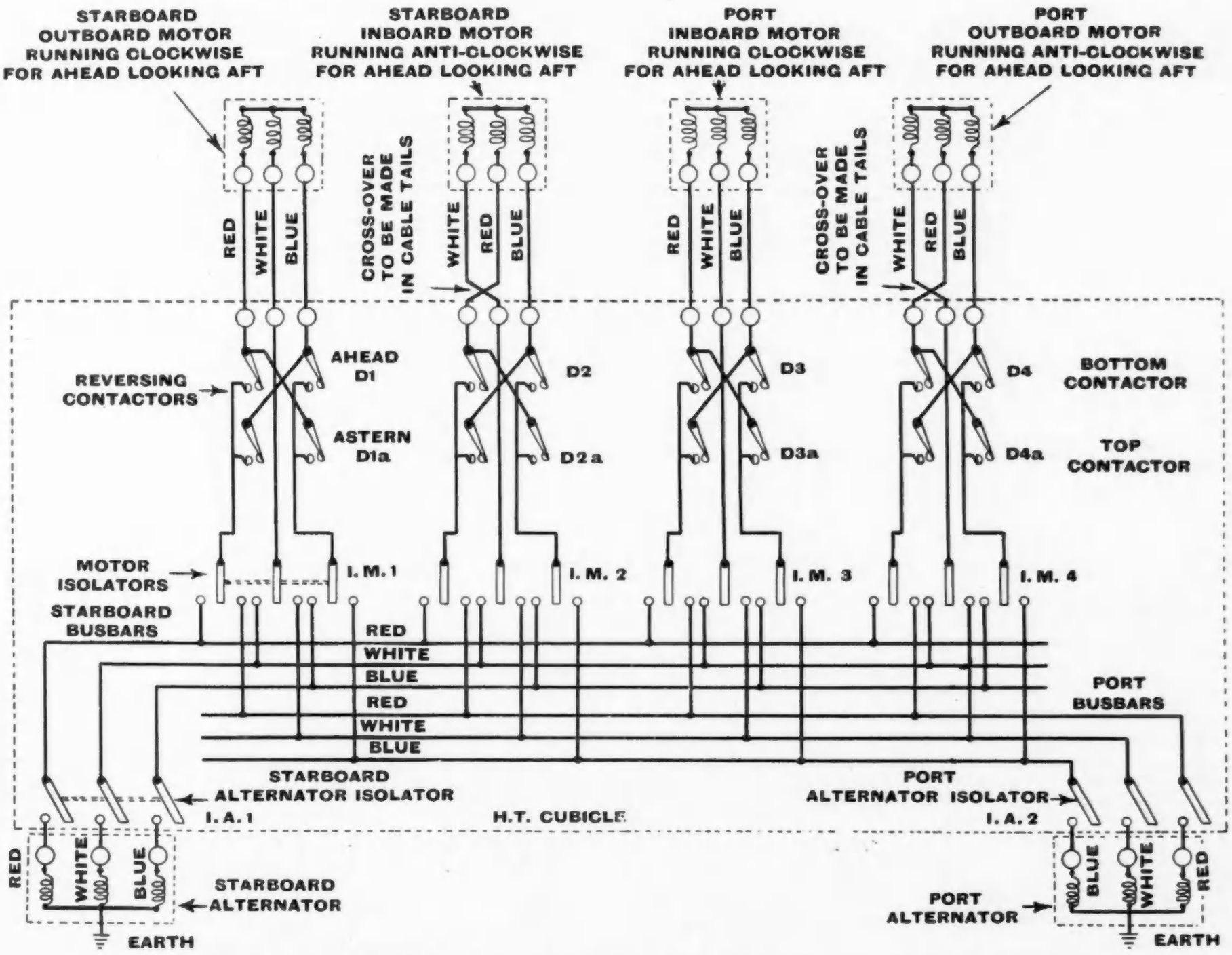

Fig. 15.—Diagram of 3-phase stator circuits for the electric propulsion equipment of the "Monarch of Bermuda."

D1 and D1a = Starboard outboard motor direction contactor.
D2 and D2a = Starboard inboard motor direction contactor.
D3 and D3a = Port inboard motor direction contactor.
D4 and D4a = Port outboard motor direction contactor.

I.M.1 = Starboard outboard motor isolator.
I.M.2 = Starboard inboard motor isolator.
I.M.3 = Port inboard motor isolator.
I.M.4 = Port outboard motor isolator.

alternator. A speed-limiter is therefore automatically brought into operation which alters the governor setting so that the speed cannot rise above 70 per cent.

In quadruple-screw ships, four alternators can be used, but in the "Monarch of Bermuda" and the "Queen of Bermuda" only two were installed, four screws being used—probably for reasons of shallow draught in ports where these ships have to trade. This arrangement of machinery might be found the most suitable for other vessels where the power is within the capacity of two alternators, because if only two motors were used their dimensions, as well as the size of shafting and propellers, might be found excessive. By a comparatively simple system of switching (fig. 15) it is possible to obtain the following methods of connection :—

(A) Two port motors to port alternator, two starboard motors to starboard alternator.

(B) Two inner motors to port alternator, two outer motors to starboard alternator.

(C) Two inner motors to starboard alternator, two outer motors to port alternator.

(D) Inner port motor to port alternator, inner starboard motor to starboard alternator.

(E) Outer port motor to port alternator, outer starboard motor to starboard alternator.

(F) All four motors to port alternator.

(G) All four motors to starboard alternator.

Under condition (A) the two motors on the port side must run at the same speed, and similarly for the starboard motors.

It was anticipated that the load taken by the inner propellers would be different from that taken by the outer ones. Conditions (B) and (C) were therefore arranged so that the inners could be run at different speeds from the outers and the load equalized. The amount of difference in r.p.m. required depends, no doubt, on the stern tube bossings, the spacing of the propellers, the lines of the ship, and the angle of the "A" brackets.

Two protective devices are required to prevent overload on the machines under some of the conditions. For conditions (D) and (E), the turbine speed must not be brought up to full value, as otherwise the motors would be overloaded. Since only half the motors are in use, the speed can only be about 70 per cent to give half torque to the propellers. A speed-limiter is therefore automatically brought into operation, which alters the governor setting so that the speed cannot rise above 70 per cent. The motors are then fully loaded in current, since they are each producing 100 per cent torque. The horse-power of each motor, however, is 70 per cent of its normal output (since the speed is 70 per cent), and the output of each alternator is only 35 per cent of normal. In addition to the speed-limiter, therefore, a load-limiter is also introduced to limit the maximum flow of steam so that the turbine cannot develop more than 35 per cent of its normal output at 70 per cent speed. This is necessary to prevent overloads on the alternators and motors when turning.

For conditions (F) and (G), the speed must again

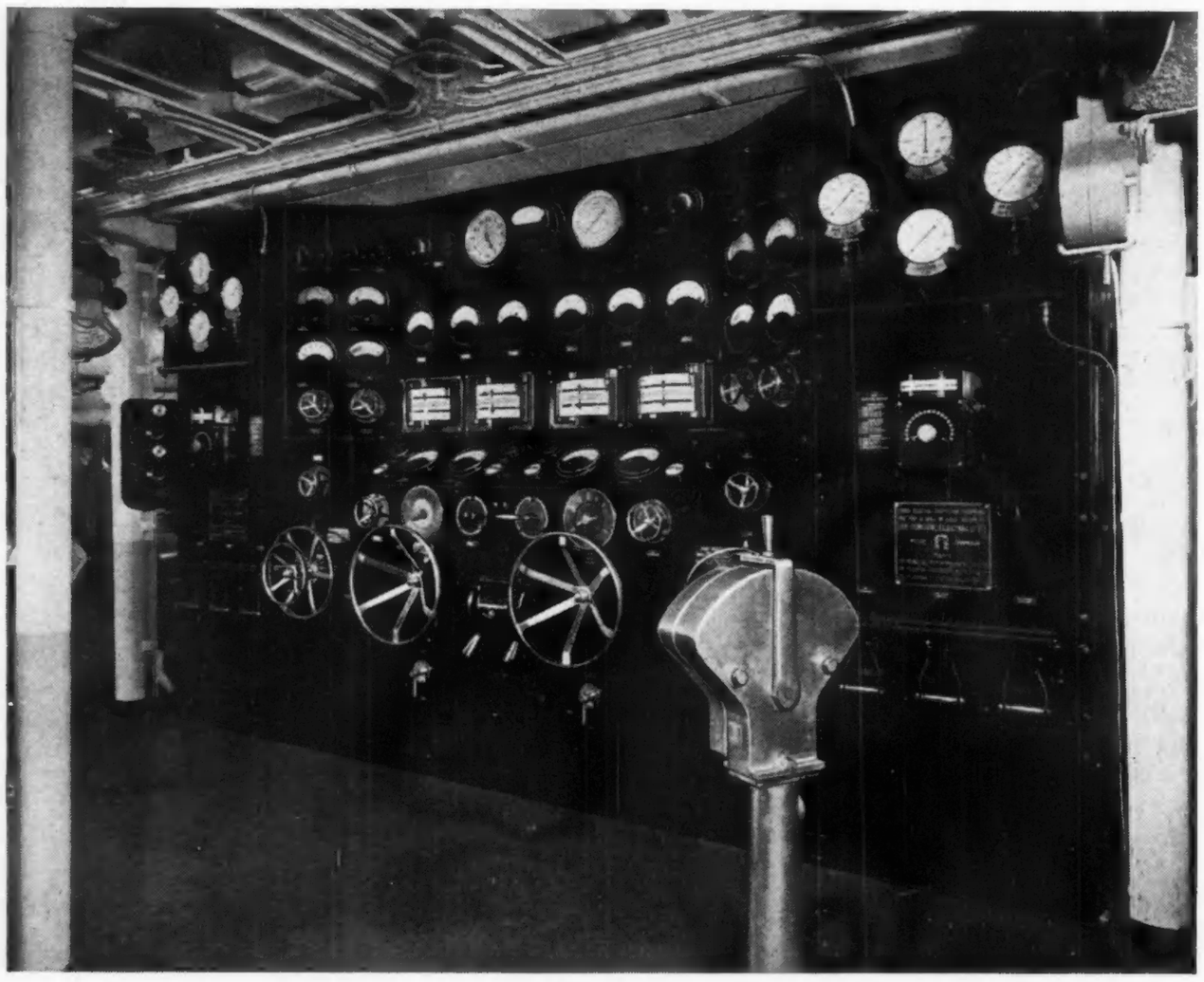

Fig. 16.—Starting platform of 3,000-volt 3-phase 50-cycle propulsion control equipment.

be limited to 70 per cent, but the load-limiter is not required. The output of the alternator is 70 per cent of normal at 70 per cent speed.

For normal running, the steam is limited so that an overload cannot be put on the alternators. If an overload tends to arise on one side of the ship, due to turning, the turbine slows down so that normal load is not exceeded. With a twin-screw ship, this means that neither the alternator nor the motor is overloaded. With a quadruple-screw ship, when one alternator supplies two motors, the total load on the two motors is limited, but not the individual load on each motor. The amount of overloading, however, is not serious, as will be seen by the following readings taken during the circling trials of the "Monarch of Bermuda."

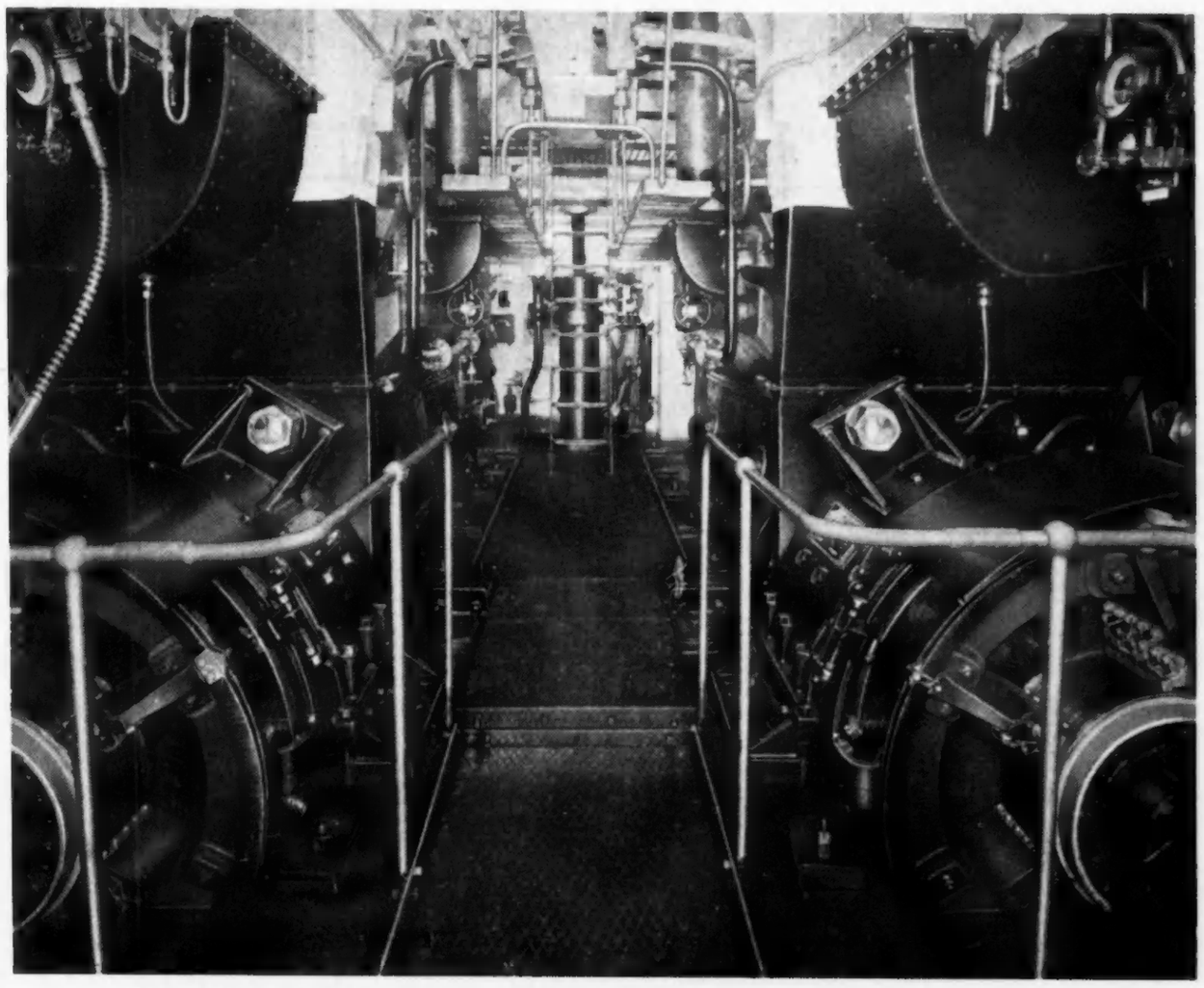

Fig. 17.—Engine room of the "Lochnevis," showing the two 425 kW, 500 r.p.m. Diesel-driven generators.

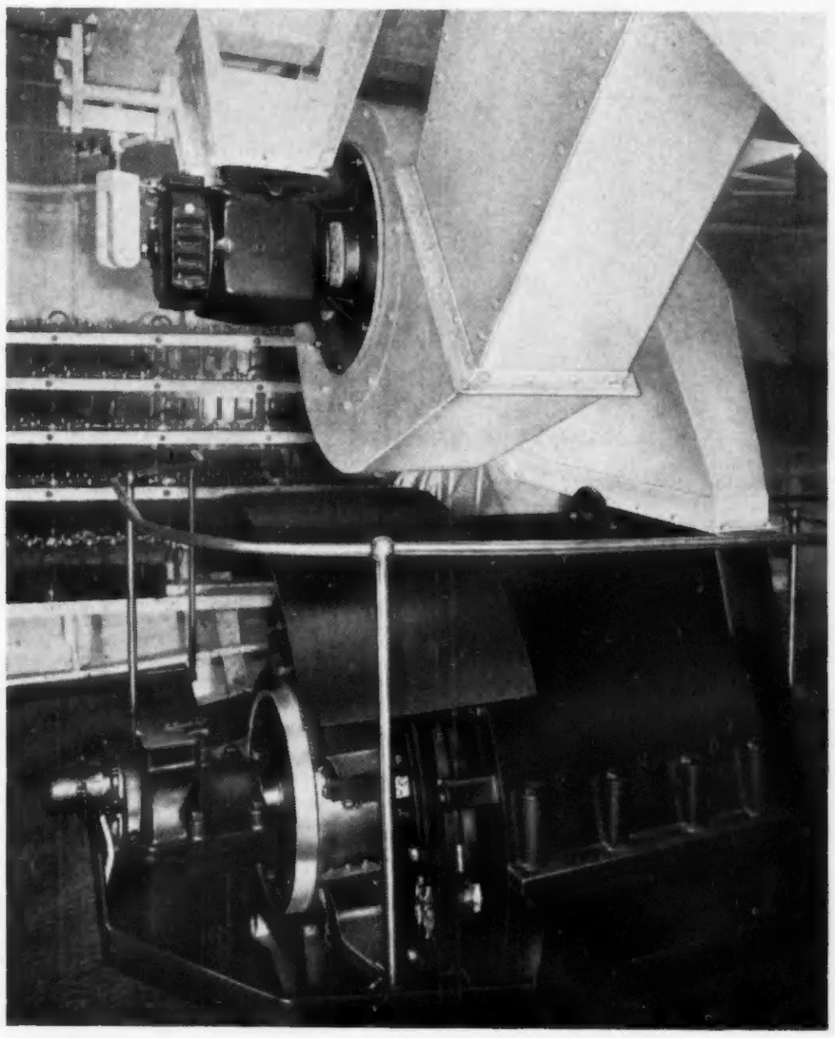

Fig. 18.—One of the 525 h.p. propulsion motors in the "Lochnevis."

(*a*) Two port motors to port alternator, two starboard motors to starboard alternator; port outer, 32 per cent of total s.h.p.; port inner, 16.5 per cent of total s.h.p.; starboard inner, 28.5 per cent of total s.h.p.; starboard outer, 23 per cent of total s.h.p.

(*b*) Two inners to port alternator, two outers to starboard alternator; port outer, 27 per cent of total s.h.p.; port inner, 17 per cent of total s.h.p.; starboard inner, 34 per cent of total s.h.p.; starboard outer, 22 per cent of total s.h.p.

In both cases the ship was turning to starboard.

Control Gear.

Since turbo-electric propulsion finds its best application in the case of large vessels, it is evident that high-voltage systems have to be adopted in order to keep the current down to minimum values, so as to limit the size of cables and switchgear. This in turn demands additional precautions, in order to safeguard the personnel, and the h.t. control gear must be of a mistake-proof nature.

It is the practice, therefore, to install all selector switches, direction switches, and connections, inside steel-plate cubicles to which access can only be obtained when everything is dead. Moreover, when

possible this gear should be arranged in a manner which will permit safely the cleaning and inspection of portions only of the h.t. apparatus whilst carrying on with the propulsion power available by means of the remainder.

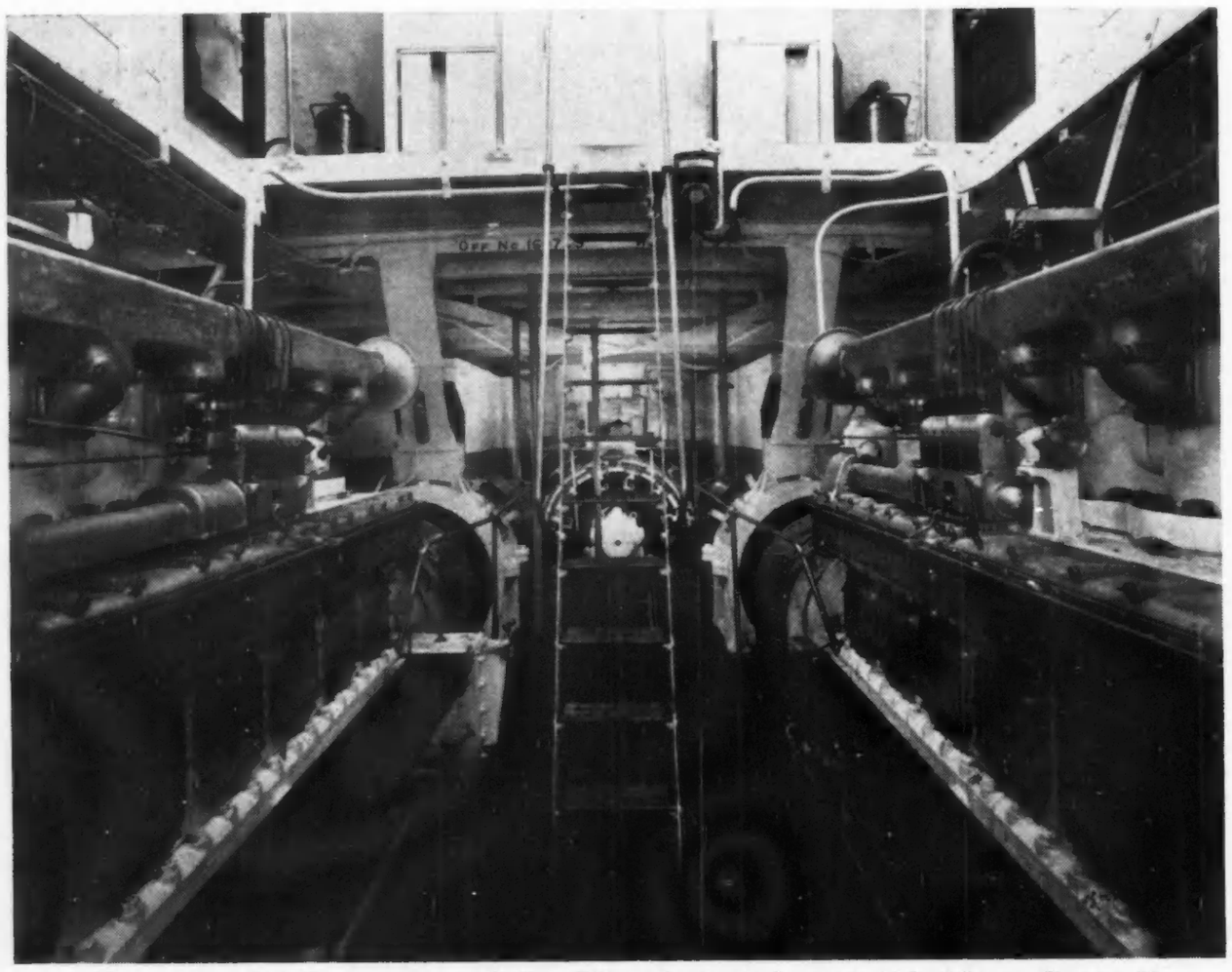

Fig. 19.—Engine room of the Diesel-electric tug "Acklam Cross," showing the two 200 kW, 900 r.p.m. Diesel-driven generators.

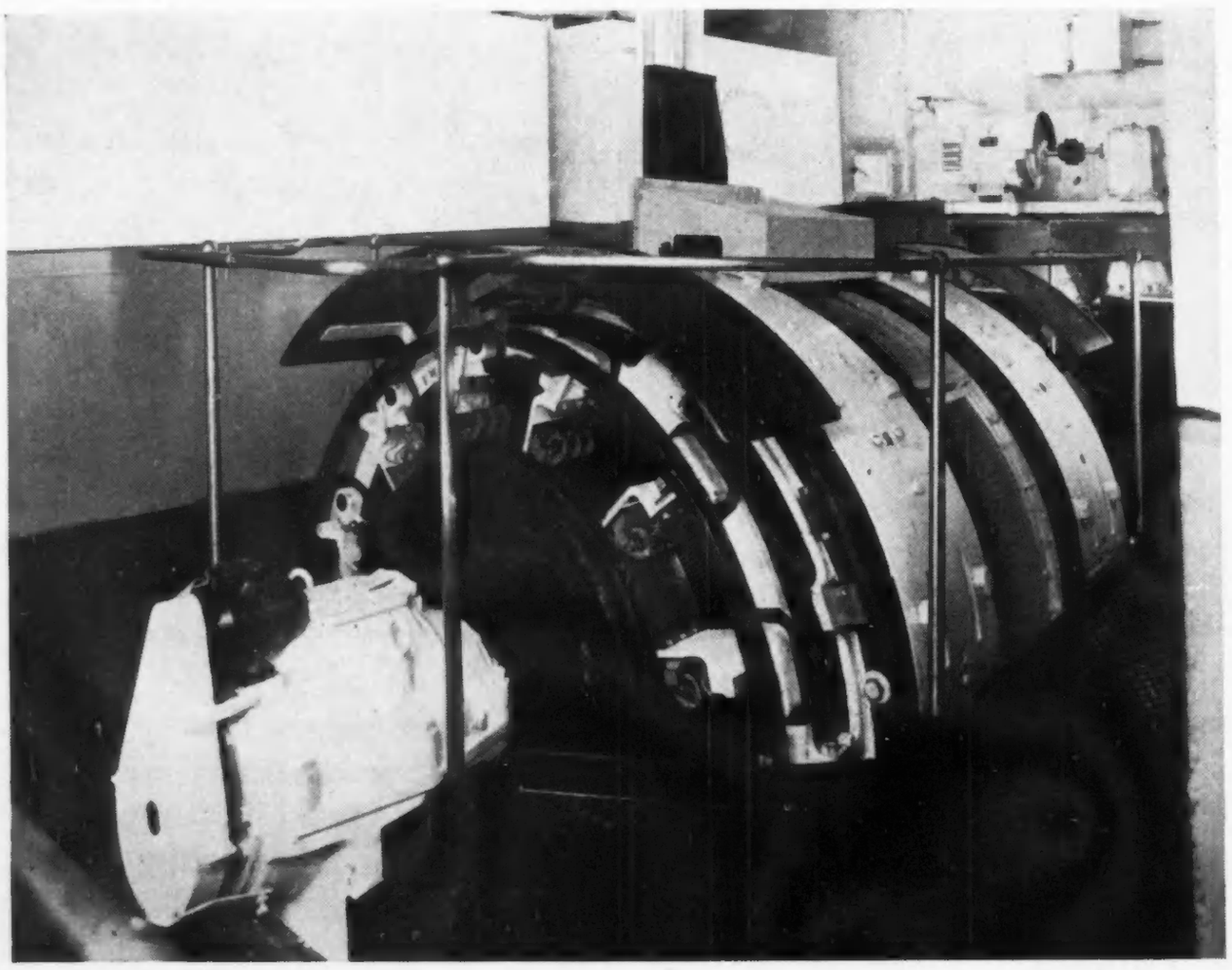

Fig. 20.—500 h.p., 115 r.p.m. double-armature propulsion motor of the "Acklam Cross."

For multiple-screw vessels, therefore, the control gear for each individual motor should be sectionalized in independent cubicles with suitable interlocks which permit of rapid isolation of any one motor and its control gear, whilst all other machines are left in commission. Furthermore, the control gear should be arranged in such a manner that rapid changes can be made in the running combinations of machines. For example, the "Monarch of Bermuda" and "Queen of Bermuda" are each fitted with four propellers each with its own motor, and operated normally from two alternators. The selector arrangements enable one man to change over this combination of machines within about $\frac{1}{2}$ minute to any other combination, and to have the propellers running again at their maximum speed, without passengers on board realizing that there has been any stoppage whatever.

The scheme of control for a.c. drive using synchronous motors is briefly as follows. Speed control is obtained by varying the frequency of supply, *i.e.* by varying the speed of the turbine driving the generator. This can be readily carried out by means of levers or wheels on the control board through the medium of oil relay systems or servo motors, which alter the governor setting of the turbine.

Since large starting and reversing torque is required for quickly accelerating and stopping the propellers and the vessel, the motors are usually started as salient-pole induction motors, afterwards synchronized at low speeds, and then adjusted to whatever running speed is required. The control gear is arranged at a central position in the engine room, and takes the form of handwheels or levers for each turbo-generator (fig. 16).

The following description of control gear refers to that used on the two "Bermuda" vessels. This constitutes the most comprehensive control gear afloat, or that is even possible, and yet it is absolutely reliable and flexible. The gear for a twin-screw vessel is correspondingly simpler. Since there are four motors any number of which may be connected to either one alternator, each motor is provided with its own reversing switches, which are electrically closed, latched in mechanically, and tripped electrically. Small handwheels are therefore provided for each motor

which decide whether such motor should be put into service or not as required.

Since there is no advantage to be gained by reversing a port outer motor whilst leaving the port inner ahead, arrangements are made so that reversal of both motors in service on the port side can be made simultaneously, and similar arrangements are provided to reverse simultaneously both motors in service on the starboard side ; but the reversal of the port side is quite independent of the reversal of the starboard side, whatever the combination of running of motors and alternators.

With the control wheel at "stop," all direction and field switches are open and the turbine governor set for about $\frac{1}{5}$ speed. Movement of the control wheel in a clockwise direction first causes the closing of the various direction switches of all motors associated at the time with that wheel, in the ahead or astern direction, according to the positions of the port and starboard direction wheels. Further movement of the wheel causes the alternator field contactor to close with double excitation. A sequence catch arrests motion at this point, and the operator pauses to allow the motors to run up as induction motors to their maximum speed at $\frac{1}{5}$ normal frequency. Since the voltage is also low, owing to the low speed, the starting-current peaks are kept down to a minimum value. Ammeters and revolution indicators show the response of the motor, and when they are nearly up to synchronism the operator passes through the sequence catch and closes the motor-field contactors to pull the motors into synchronism. A second sequence catch arrests motion again, and when the motors are synchronized, as shown on the indicating instruments, the operator passes through the second sequence catch and closes the field contactor of a negative booster set which reduces the alternator field to normal running value.

Up to this point the control wheel has made one complete revolution, and the switching operations have all been carried out at $\frac{1}{5}$ speed. The wheel can now be turned through a second complete revolution which has effect only on the setting of the turbine governor, permitting this to be raised up to full speed. Fig. 21 indicates the variation in propeller speed which occurs during the full-speed reversal of a turbo-electric liner.

Reduction in speed is carried out by rotating the control wheel in an anti-clockwise direction, in which case there is no hold-up by the sequence catches. The first return revolution of the control wheel reduces the governor setting to $\frac{1}{5}$; the second revolution opens all the field contactors and energizes a 5-sec. time-delay, which in turn permits the direction switches to open only when the heavy induced current due to the breaking of the fields has died away. The direction switches may then if desired be reversed and the starting sequence repeated as described above.

An alternative direct mechanical control is provided for direction switches and field contactors, which is instantly available in the event of failure of the electrical closing operations, and this mechanical operating mechanism is fully interlocked to prevent mal-operation in service. Reference has already been made to the speed- and load-limiting features.

In the P. and O. liners "Viceroy of India," "Strathaird," and "Strathnaver," the scheme of control is on the same general principle, but all these vessels are twin-screw only, and the control is carried out by three levers for each side of the vessel. These levers are interlocked to prevent incorrect operation. One lever controls the direction of rotation, one lever closes the field contactors, and one lever controls the speed by operating on the governor setting. In these ships also the switching arrangements are electrically operated, but the levers also

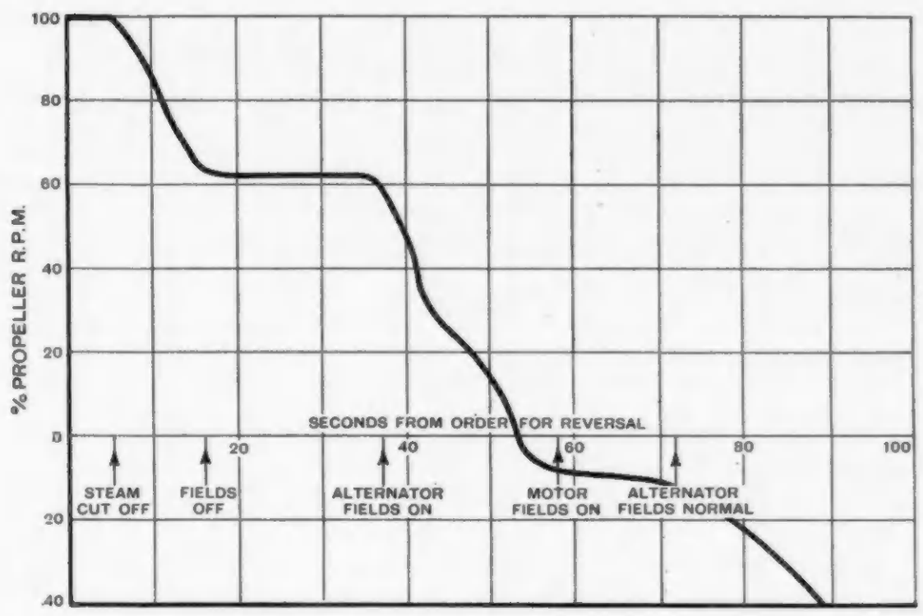

Fig. 21.—Full-speed reversal of turbo-electric vessel.

actuate a mechanical follow-up gear, which would close the contactors mechanically by the same movement if the electrical closing failed to function.

DIRECT-CURRENT DIESEL-ELECTRIC DRIVE.

Advantages.

Since success has attended the use of Diesel engines for driving the propellers directly, it is not to be wondered at that the attention of shipowners has been directed to Diesel-electric drive. The addition of the electrical transmission has enabled economical values to be selected for the speeds of the engines and the propellers. A further invaluable advantage is found in the fact that the engines run in one direction only at constant speed, and are not subjected to frequent starting and stopping when manœuvring is being carried out.

Disadvantages.

The limitation of output of d.c. Diesel-electric propulsion lies in the value of the current necessary, since very high voltages are not desirable. This

current necessitates very large commutators and heavy switchgear and cables. It is also found that the number of engines required is sometimes excessive.

Control.

In regard to the method of control, the Diesel-electric is of course far superior to the direct Diesel drive. In the former the whole of the speed regulation of the propeller in both directions is effected by controlling the comparatively small currents in the fields of the generators or motors.

Ward-Leonard system.—Most of the ships already built with Diesel-electric drive are controlled on the Ward-Leonard principle. The motors are excited in one direction from a separate source of supply, and the generators are also separately excited, but a regulator varies the strength of their field from a

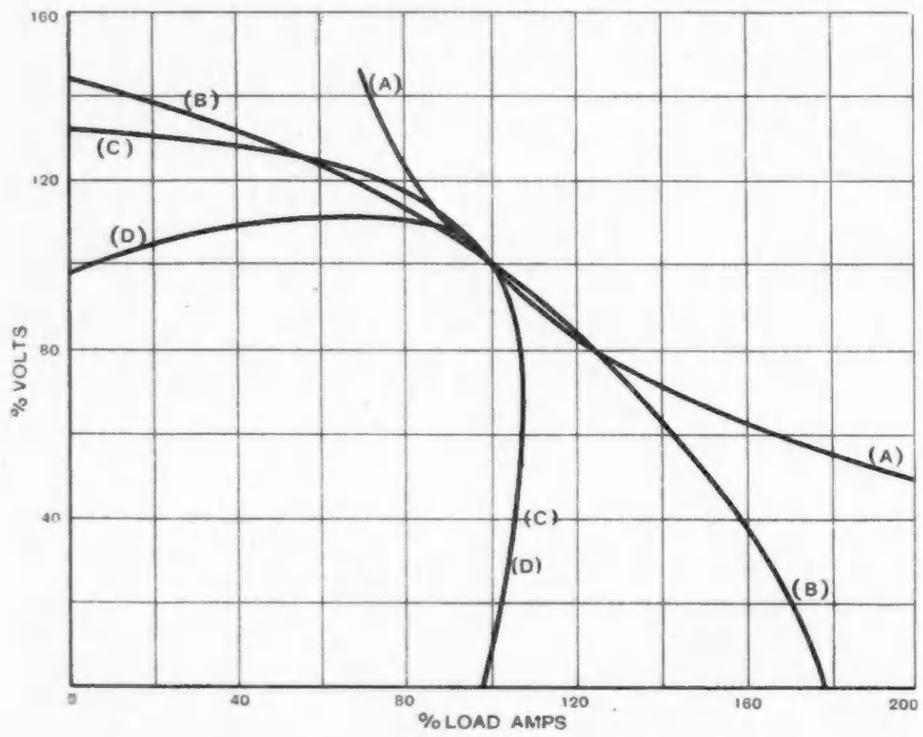

Fig. 22.—Generator characteristics for Diesel-electric propulsion.

(A) Theoretical characteristic for constant engine power.
(B) Constant-power system.
(C) Constant-current system.
(D) Austin system.

maximum in one direction to a maximum in the other. For small twin-screw boats using two engines, it is sometimes necessary to run both motors from only one engine, in which case arrangements may be made to reverse the motor fields after reducing the generator voltage to zero. At starting a small excitation is applied to the generator, producing a small voltage which sends a current through the motor armature. Since the motor field is excited, a torque is exerted which turns the propeller. As the speed rises, the field of the generator is progressively strengthened until the desired speed is obtained. It will be seen that if the generator field is strengthened too quickly before the propeller speed has had time to rise, excessive currents may flow which may cause dangerous sparking at the commutators, and possibly overload the engines.

The two principal methods of control on the Ward-Leonard system are known as the "direct" and the "follow-up" methods.

Direct control.—With a cam-operated controller or a face-plate controller, the regulator in the generator field is directly operated from the bridge by means of mechanical drive, the controller taking the form of an ordinary ship's telegraph. The regulator has a comparatively small number of sections (eight or ten) in the case of the former, but a much larger number in the case of the latter type.

Follow-up control.—The follow-up method of control operates on the "Wheatstone bridge" principle. The telegraph on the navigating bridge moves an arm on a potentiometer regulator. When this arm is displaced from the position of the corresponding arm of another potentiometer mounted on the main regulator, a circuit is completed which starts a small motor driving the main regulator and keeps it running until the arm on the second potentiometer again corresponds to the arm on the bridge. The motor then stops. Thus the regulator in the generator field cannot possibly be operated too quickly, however rapidly the telegraph is moved.

Propeller-racing.—In the Ward-Leonard system, if the generators are shunt-wound or lightly compound-wound, there is no danger of the propellers racing in a heavy sea. If the load comes off a motor, its speed rises a small percentage until its back e.m.f. is equal to the voltage of the generator, and the current falls to practically zero.

Over-power and reverse-power.—Since the current flowing in the generator and motor armatures depends on the difference between the generator e.m.f. and the motor back-e.m.f., a small change in one of these e.m.f.'s makes a large change in the current. It is therefore necessary to see that the generator e.m.f. is not altered so quickly that the motor back-e.m.f. cannot follow. In small vessels it has been found that the propeller speed can change so rapidly that very little over-power is produced when the telegraph is suddenly thrown from "stop" to "full ahead," and very little reverse power when it is thrown from "full ahead" to "full astern."

In order to avoid the necessity of providing the engines with a large margin of power, some form of over-power relay may be fitted which inserts a resistance in the generator fields if the power taken exceeds the normal power of the engines. In this way a heavy current may be taken at starting, when the voltage is low, but the current is limited when the voltage has risen.

Constant-current systems (described later) automatically take care of this question of overloading to a certain extent.

An alternative system which definitely prevents overloading during turning is called the "constant power" system (curve *B*, fig. 22). This system

consists of a separately-excited generator with a heavy counter-compound winding which has a drooping characteristic and can be so designed that the power supplied (volts × amps.) is approximately constant over a small range, and is equal to the engine power. Thus an overload due to turning the ship is prevented by the fact that as the voltage falls the current rises. A disadvantage of this generator is that the open-circuit voltage is rather high, so that there is a tendency towards propeller-racing in rough seas. This can be overcome by means of a voltage relay which inserts resistance in the generator field if the voltage exceeds a predetermined value.

For large vessels it may be found advisable to adopt the use of motor-driven field regulators, adjusted to operate over their whole range from "full ahead" to "full astern" as rapidly as possible, and to provide over-power and reverse-power relays (which can readily be combined in the same relay). Reverse power up to the value which will absorb the friction and driving losses of the Diesel engine is permissible, but any further power would tend to speed up the engine and must be prevented.

The reverse-power relay is arranged, therefore, to open the circuit of the motor driving the regulator, and prevent further reduction of forward voltage, or further increase of reverse voltage, until the vessel has lost sufficient way to reduce the value of reverse-power feed. The over-power relay can be similarly arranged to hold up the motor-driven regulator or alternatively to insert additional resistance in the generator field, thus reducing the voltage and consequently the speed, and therefore the load taken by the propulsion motor. By adjusting the values of relay settings, etc., slowing-down of the Diesel engines due to overload can be definitely prevented.

Switching.

Single-screw.—In a single-screw ship it is usual to use more than one engine and generator, as a safeguard against breakdown. The motor may also have a double armature. All the armatures are connected in series and provision can be made for immediately cutting a generator out of circuit in case of failure.

This can be done by providing a make-before-break change-over selector switch, with suitable auxiliary contacts which first open the field of the generator to be isolated. Sequence catches then arrest motion of the switch in order to permit the residual field to die away, after which the operator completes the movement, temporarily short-circuiting the generator armature, completing the propulsion circuit through a direct connection, and finally opening the generator armature-circuit. Auxiliary contacts on the generator field contactors are arranged to open a short-circuit across suitable resistance in the motor fields, in order to permit them to take up, on the reduced voltage available from one generator, a speed which will absorb the full horse-power of that engine.

If there are two engines and one breaks down, the voltage supplied to the motor is halved and the propeller runs at half speed. The horse-power required at half speed, however, is only one-eighth of the full-load horse-power, so that the propeller must be speeded up to about 80 per cent of full speed. This brings the load up to half full load, which is the full output of one engine.

Where more than one generator is running on one propeller, arrangements can be made, under a patented system, for automatically cutting out a failing generator and adjusting the motor field value to suit the full output of the remaining engine or engines. For this purpose a special differential relay is provided, which balances the voltage of one generator against that of another in the same system, a contact on the lower-voltage side of the system being provided to open the generator field contacts of the failing machine, thus leaving a dead armature in the circuit, which can then be isolated by means of a change-over make-before-break switch, as described above. Under-speed contacts on a faulty engine can also be arranged to open the field circuit of its co-related generator. Thus a failing engine can be removed from service with the remaining power uninterrupted.

Twin-screw.—Under another patented system of protection, similar arrangements will permit the removal of a failing engine on twin-screw systems, without total loss of power on either side of the vessel. This is done by normally operating the two sides of the vessel independently, but with the system connected on a 3-wire scheme, having an automatic switch inserted in the mid-wire connection. Failure of an engine on, say, the port side is arranged to operate either a reverse-power relay or an under-speed device on the port generator, which will trip the generator field contactor and also open the mid-wire circuit breaker. The two motors are then left in series with each other, operating from the starboard generator through the dead armature of the port generator, which can be isolated by means of a change-over make-before-break switch.

This scheme is possible with twin-screw vessels operating with two engines, when the reversal is carried out at the motor field, as the flow of current is always in the same direction. It should be noted that the mid-wire carries current only when the two motors are running at different speeds.

For normal running in twin-screw vessels, it is usual to keep the port or starboard sides separate. It is advisable, however, to be able to run both motors in series with one generator if required. In this case both propellers must run at the same speed, but one can be ahead and the other astern.

When the two motors are connected in series, a

difficulty arises with regard to racing. For example, the port propeller may come out of the water before the starboard. The port motor will then begin to speed up and the current will be reduced. The starboard motor will thus fall in speed, until finally there is a tendency for it to reach the trailing speed of about 70 per cent. The port motor will therefore tend to reach 130 per cent of the full speed available with one engine in order that the sum of the counter-e.m.f.'s of the motors may equal the generator voltage.

Constant-Current Systems.

Another system which has been proposed instead of the Ward-Leonard is the constant-current system (see curve *C*, fig. 22). In this system the machines are so designed that a practically constant current flows in the main circuit. Speed regulation is effected by varying the motor field. At starting, the motor field is zero, so that the armature current produces no torque. As the motor field is strengthened, the torque is increased and the speed of the propeller rises. The generator voltage automatically rises with the propeller speed.

There are four principal methods employed on the so-called constant-current system.

(*a*) The first uses the 3-field generator, which has a separately excited winding, a self-excited winding, and a counter-compound winding. This machine gives a practically constant current over the working range, but the open-circuit voltage is rather high.

The condition of the propeller coming out of the water is entirely different from that of the Ward-Leonard system. The generator is designed to give constant current, and therefore continues to supply this current. The motor therefore continues to exert torque with the propeller out of the water. Consequently, the speed rises until the counter-e.m.f. of the motor is equal to the open-circuit generator voltage. It is a simple matter, however, to arrange a relay which will open the separately-excited generator field when the propeller speed rises a small percentage above the normal. This cuts down the current, and with it the torque.

With the 3-field generator it is possible to arrange the windings in such a way that the current carried when the voltage is reversed is considerably reduced. This condition occurs when the telegraph is moved quickly from "full ahead" to "full astern." When the motor field is reversed with the motor still running ahead, the voltage is reversed and power is taken from the propellers and absorbed in driving the engines. Under this condition, the generator can be designed to take such a current that the reverse power is only that required to run the engines light at their normal speed.

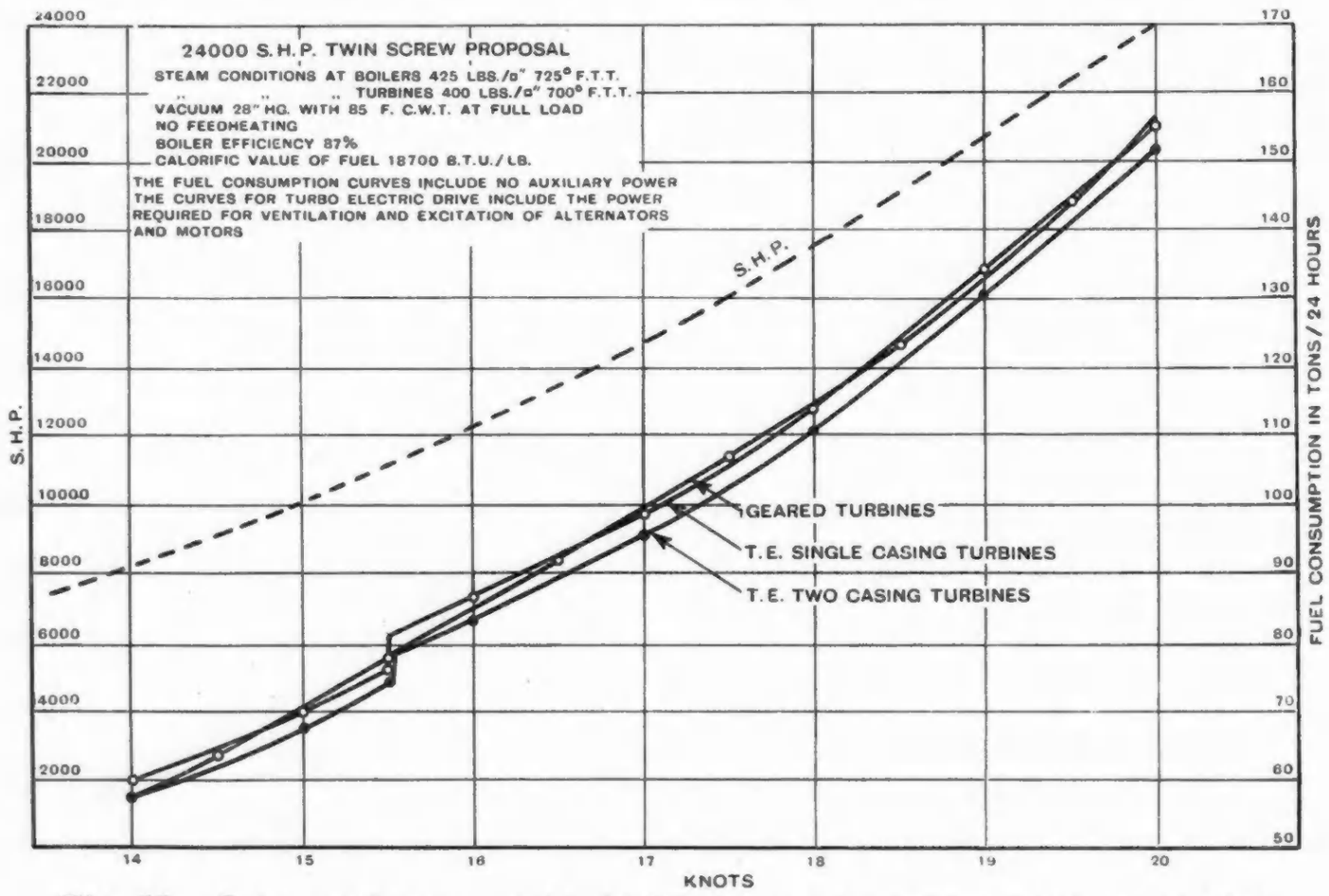

Fig. 23.—Consumption curves for 24,000 s.h.p. twin screw vessel, comparing two turbo-electric drives with a geared turbine drive.

(*b*) In the Austin system (curve *D*, fig. 22) the generator has specially-shaped pole shoes. The characteristic is similar to that of the 3-field generator over the working ranges, but the open-circuit voltage is lower. It is claimed that the speed-rise with the propeller out of the water is not excessive.

(*c*) A third system employs standard generators and uses a current relay which automatically regulates the generator field. If the current tends to rise, the generator field is weakened, and vice versa. With this system it is necessary to limit the generator voltage in order to prevent racing.

(*d*) A fourth system has been called the "con-

trolled current" system. In this system a 3-field exciter is used, the counter-compound winding of which carries the main motor current. The characteristic is exactly the same as that of the 3-field generator. Regulation is effected on the exciter field instead of on the generator field.

In a single-screw ship with a constant-current system, more than one generator can be used, as for the Ward-Leonard system. In the 3-field and the Austin methods, the generators are connected in parallel, and in the relay method they are in series.

In a twin-screw ship, the port and starboard sides can either be kept separate, or the propeller motors can be connected in series. The latter method presents some advantages, and the two motors can be controlled entirely independently in speed and direction by means of the field regulators. In a rough sea, however, the method may involve a difficulty. If the propellers are coming out of the water they may not come out at the same time. When one propeller comes out, it is necessary to reduce the armature current and prevent racing. Since the two motor armatures are in series, however, the current in the other is also reduced and the driving power of the ship is lost. When the first propeller has entered the water again, the second may have come out, and the driving power is again lost. In this way, the power to drive the ship may only be available for a short proportion of the time.

Response.

There is an interesting point with regard to the operation of the Ward-Leonard and constant-current systems. With the Ward-Leonard, the propeller speed quickly follows the telegraph orders. If the telegraph is changed from "full ahead" to "half ahead," the regulator is quickly changed to its "half ahead" position. Reverse power will flow from the motors to the generators, and the propeller speed will be quickly reduced.

The same change of order with the constant-current system will quickly reduce the motor-field regulator to the "half ahead" position. The torque is therefore reduced, but it remains in the same direction. The propeller speed will fall to slightly above the trailing speed and will gradually fall to half speed as the ship loses way. This difference in response will of course be readily recognized by the navigator. If a quicker response is required with the constant-current system, it is only necessary to put the telegraph "astern" until the ship loses way, and then come back to "half ahead."

CONCLUSION.

It is very gratifying to know that the standards and margins that the electrical industry has observed for many years have enabled marine engineers to accept electrical equipment without any criticism as to its reliability. It has taken a long time to become established on board ship, and this has only been achieved by the use of the best workmanship and material, by the thorough manner in which electrical designers have tackled the problems involved, and by the co-operation of the marine engineers.

* * * * *

Subsequent to the reading of this paper, considerable discussion ensued regarding the comparative efficiencies of turbo-electric and geared turbine propulsion.

Fig. 23 shows consumption curves which have been prepared from the actual figures put forward by various engine makers in tendering for a certain ship. They show that under certain steam conditions turbo-electric may be even more efficient than geared turbine propulsion. With these steam conditions and the choice of turbine and propeller revolutions that the flexibility of the turbo-electric drive allows, the maximum efficiency is obtained.

Notes on Modern Electrical Measuring Instruments

A BRIEF SURVEY OF THE TYPES OF ELECTRICAL INSTRUMENT USED TO-DAY.

By H. COBDEN TURNER

Manager, Salford Electrical Instrument Works of the G.E.C.

Not many years ago the use of electrical measuring instruments was confined to comparatively few obvious applications. At the present time, due to the vastly improved performance of the instruments now produced, their scope has been considerably widened. They are widely used industrially for many diverse measurements, some of which indeed have no apparent connections with electrical quantities.

In the accompanying article each type of instrument is briefly described and the improvements it embodies are outlined. Indications are given as to the best choice of instrument for any particular duty and, finally, the trend of design is discussed.

GENERAL.

OF the total number of electrical instruments used, three-quarters are of either the moving coil or the moving iron type. The remaining quarter is, however, equally important and finds many diverse applications of a somewhat specialised nature.

In discussing the various types, it will be of advantage to review the fundamental electrical phenomena involved. These phenomena may be divided into four classes :—

1. Electromagnetic
2. Electrothermal
3. Electrostatic
4. Electrochemical

The corresponding types of instrument are as follows :—

1.	*Electromagnetic.*	Moving coil.
		Moving coil with rectifier.
		Polarised moving iron.
		Moving iron.
		Dynamometer.
		Induction.
2.	*Electrothermal.*	Hot-wire or expansion type.
		Thermo-e.m.f. type.
		Thermo-bimetallic type.
3.	*Electrostatic.*	Electrometers.
		Electrostatic wattmeters.
		Electrostatic voltmeters.
4.	*Electrochemical.*	Ampere-hour meters (quantity)

It will be appreciated that the characteristics of instruments based on different electrical phenomena will vary considerably, and whilst for some purposes several types of instrument based on different phenomena may appear equally suitable, a critical survey will show that for a given purpose one instrument will usually have features of superiority over the others.

All these types of indicating instrument have, however, this in common, that their working depends on the balancing of two forces, termed the operating force and the restraining force. A spring usually provides the restraining force whilst the operating force is provided by the action of the current, voltage or other quantity to be measured. The forces take the form of torques and, in general, the higher the torque the better the instrument.

The properties and salient features of these various types may now be considered.

MOVING COIL INSTRUMENTS.

The moving coil instrument consists of a permanent magnet with two air gaps in which a pivoted coil can rotate. The control or restraining force is supplied by two springs which also carry current to the coil. The interaction of the magnetic field due to the permanent magnet and that due to the current in the coil causes a

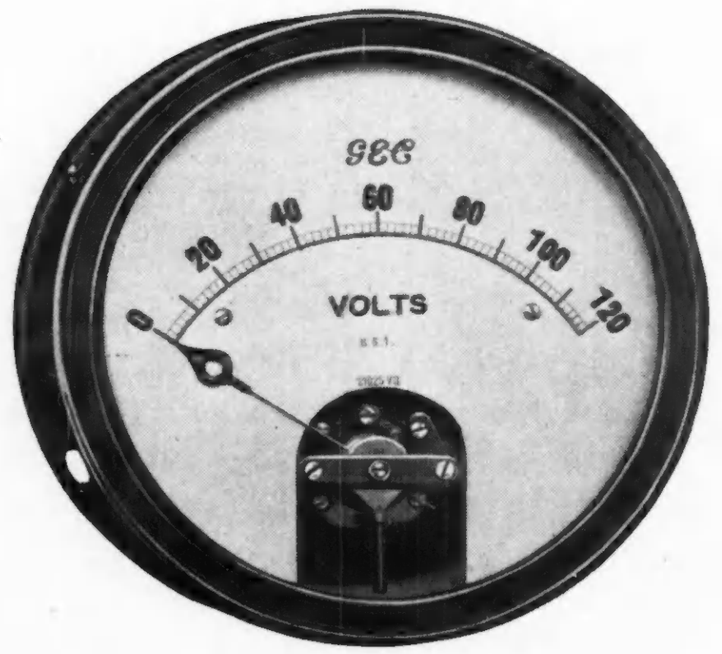

Fig. 1.—Typical 6-inch moving coil voltmeter.

torque to be applied to the coil. A pointer is carried on the pivoted coil and indicates on a fixed scale.

The permanent magnet provides by far the greater component of the force required as the torque depends on the product of the flux due to the permanent magnet and that due to the moving coil. In this way the electrical consumption required from the circuit is made small; smaller, in fact, for a given torque than is necessary with any other type, with the exception of the electrostatic voltmeter.

The presence of the permanent magnet renders the instrument polarised, *i.e.*, the direction of motion of the coil depends on the direction of the current.

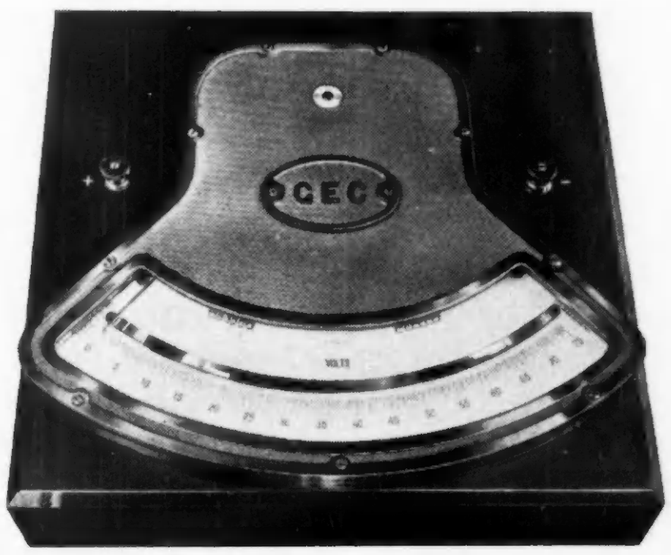

Fig. 2.—Sub-standard type moving coil voltmeter.

This property is made use of for centre-zero instruments in which the direction as well as the magnitude of the current is shown.

This type is practically always used for direct current work; its accuracy can be at least as good as that of any other type.

The moving coil instrument lends itself to easy calculation for close approximations, and, in consequence, the design has with one exception remained unchanged over the past 10 years or so. The exception is the "Cirscale" of Record, in which the shape of the magnet is altered so that the ends of the coil cut the magnetic flux instead of the sides, thus providing a long scale arc. Instruments of this type have a scale arc of about 270°. Other problems, however, are introduced by this feature.

One important improvement is the use of modern high-retentivity steels such as cobalt-steel.* With these alloy steels, a given magnetic flux can be obtained with a smaller magnet. This has given rise to the misapprehension that more powerful magnets are now available: This is only true if the qualification is added—"for a given volume of steel," otherwise there would be nothing to prevent the making of a magnet having any required flux with any magnet steel.

For a given total flux through the moving coil of an instrument any suitable magnet steel may be used, but the proportions of length to cross section will vary with the particular steel used. By replacing tungsten steel by 35 per cent cobalt-steel, the original length of steel can be reduced to about one-third, but the section must be increased to about $1\frac{1}{4}$. If this is not done, the magnet will not work on the best part of the B_{rem} H_c curve, and so will not operate at (BH) max. The new nickel-aluminium steels, which have a very high value of (BH) max, may be applied to instruments, but such application is not easy, as the length has to be reduced considerably for a given section, necessitating very short and thick magnets.

Pivoted instruments may now be obtained with ranges as low as a few microamperes due to improvements in general design such as ensuring a minimum weight of moving element, providing a powerful magnet in a given space by using a 35 per cent cobalt-steel, also as a result of research work on pivots and jewels with the object of obtaining minimum friction and conversely a lower minimum allowable torque for a given weight of movement.

Until some ten years ago the usual scale arc of moving coil instruments was 90° (with the exception previously noted). To-day, scale arcs are increased to 110 or 120 degrees, giving scale lengths equal to the dial diameter for arcs of about 120° and a suitable pointer length.* Increase of scale-arc has been obtained by re-designing the magnet poles, thus leading to a higher leakage flux which, although wasteful, conduces to permanency of the magnet and continued accuracy of the calibration.

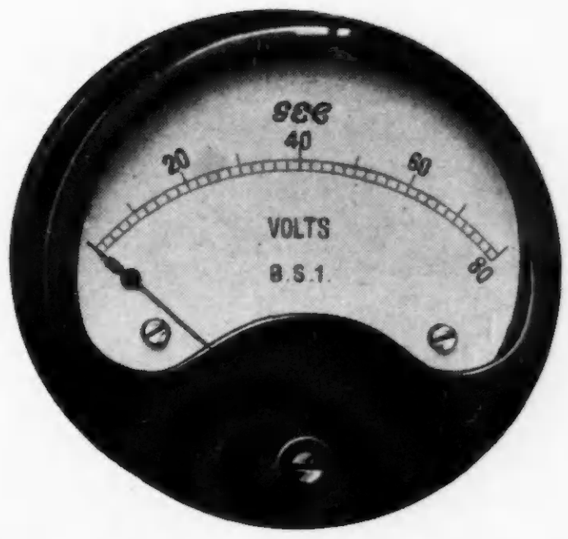

Fig. 3.—2½-inch moving coil voltmeter.

RECTIFIER INSTRUMENTS.

The development of the metal rectifier in recent years has served to make the moving coil movement available for alternating current. The method is relatively simple and enables the excellent torque and damping characteristics of the moving coil instrument to be used for a.c. measurements. On the other hand, it has troubles of its own, the chief of these—and a very serious one—being the waveform error, due to the fact that a moving coil

* See Appendix C.

* See Appendix B.

instrument reads the mean value of a rectified current, whilst the r.m.s. value is the one required in usual practice.

In this way, an error as great as 10 per cent may be introduced, which seriously limits the use of rectifier instruments for accurate work. The property of small watt consumption inherent in the moving coil movement, however, opens up a definite field of use where very low ranges of current and voltage and circuits of low power are dealt with, for all of which the usual a.c. instruments are handicapped by their higher consumption.

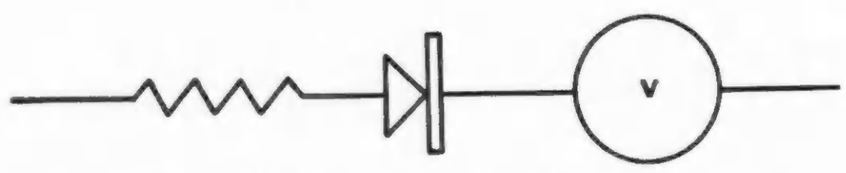

Fig. 4.—Application of a rectifier to a moving coil Voltmeter.

Fig. 5.—Illustrating half-wave rectification obtained with rectifier as shown in fig. 4.

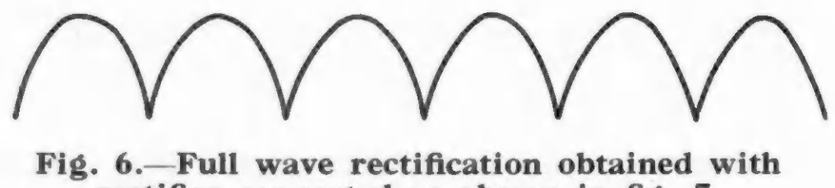

Fig. 6.—Full wave rectification obtained with rectifier connected as shown in fig. 7.

The wide frequency range renders this combination highly suitable for audio-frequency measurements, while it has ideal characteristics for those cases in which the mean, as distinct from the r.m.s., current is to be measured.

The application of the rectifier to the moving coil needs consideration. A single rectifier element, (fig. 4) in series with the movement is unsatisfactory as in the first place only one half of the wave is rectified (fig. 5) and, secondly, the rectifier has to withstand the full peak voltage of the circuit on the non-conducting half-cycles. As instrument rectifiers are only intended for about half a volt per element, it will be seen that a number of them would be required to deal with relatively high voltages. Full-wave rectification (fig. 6) by means of four rectifier elements is therefore usual, the rectifiers being connected as in fig. 7.

Error due to wave-form is exemplified by fig. 8, where (*a*) shows a sinusoidal wave for which the form factor, *i.e.*, the ratio of root-mean-square (r.m.s.) value to the mean is 1.111. A peaked wave as in fig. 8 (*b*) has a higher form factor, while for flat-topped waves the value would be lower. It should be noted that smoothed rectified current approximates to a steady d.c., and the ratio approaches unity. As the rectifier instrument is usually calibrated in r.m.s. units, although reading the mean value, this variation of form factor may lead to an error of as much as 10 per cent. It is not generally realised that the rectifier itself modifies the current wave-form unless the external resistance is very low, even when the applied voltage wave-form is sinusoidal.

Rectifier instruments have been available commercially for about ten years and their reliability has been greatly increased during the period. An advance has also been made in reducing the size of the rectifier so that the capacitance is less and the frequency range correspondingly increased.

With early instruments, the upper frequency limit was about 4000—6000 cycles per second, but now 50,000 cycles per second is attainable for milliammeters. Voltmeters are usually less suitable at high frequencies as their resistances are not generally sufficiently non-reactive. This does not rule out their use however, as suitable resistances can be obtained, but in general they are not quite so cheap to produce as the usual commercial resistance bobbin which serves for moving coil and moving iron instruments.

POLARISED MOVING IRON INSTRUMENTS.

The polarised moving iron type is a very early form of electromagnetic instrument. It comprises a small pivoted iron vane mounted near the poles of a small magnet, which provides a restraining force, while a coil with its axis at right angles to that of the magnet provides a deflecting force. The moving iron takes up a position with its axis along the resultant of the permanent and the electromagnetic fields. As the permanent magnet provides the restraining force, no springs are necessary and the required damping is obtained by the permanent

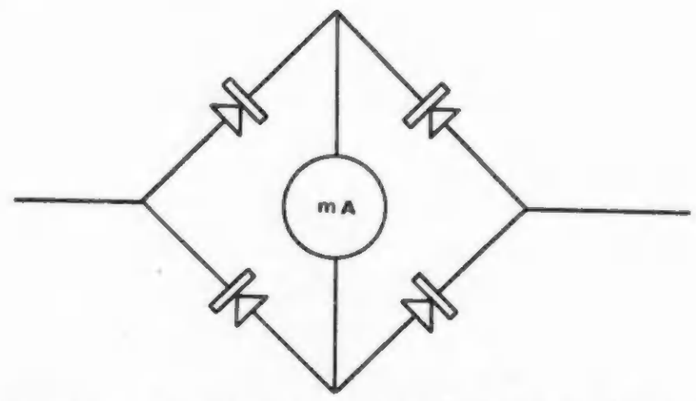

Fig. 7.—Arrangement of rectifier to give full wave rectification.

magnetic field. Being polarised by the permanent magnet, the instrument will only measure direct current.

This instrument was in the early days extensively employed, but latterly it has been restricted almost entirely to motor car dashboard use, where its simple construction has made it particularly suitable and where accuracy is of secondary importance.

There has recently been a revival in the demand for this type of instrument for cheap radio test sets.

MOVING IRON INSTRUMENTS.

The moving iron instrument satisfies nearly all requirements for a.c. voltage and current measurements, both commercial and precision. It is cheap to manufacture, and though early models were crude and inaccurate, and had large hysteresis errors, present-day instruments are capable of precision accuracy, both on a.c. and on d.c.

In these instruments torque is proportional to the rate of change of inductance with deflection; the maximum torque being obtained when the inductance of the winding approaches zero, *i.e.*, when the pointer is at zero. In practice this is not, of course, absolutely attained, but from this theoretical consideration is derived the fact that the coil should be so proportioned as to possess minimum inductance for a given value of exciting ampere-turns. The change of inductance is brought about by the movement of a piece of iron carried on the pointer spindle, usually within the field of the exciting coil. The movement of the iron varies the inductance of the coil as the pointer rotates.

Two general forms exist, each of which has its own advantages. The first is the attraction form having one piece of iron only, which is attracted into the coil to increase the inductance. The second is the repulsion form which has two pieces of iron, one fixed and one moving. These are mutually repelled, resulting in rotation of the spindle carrying the moving iron. The second form is that commonly used.

The consumption of a moving iron instrument

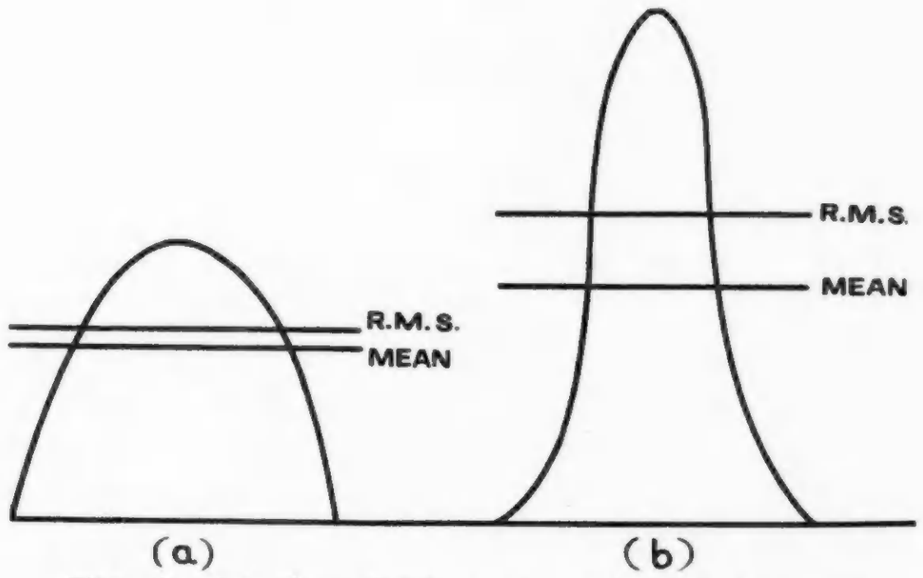

Fig. 8.—(a) sinusoidal wave: (b) peaked wave.

is higher than that of a moving coil type of equal torque, and so, whilst the moving iron will read accurately on direct current, its use is less general because of its higher consumption, and because of its inferior damping and non-linear scale. The lower part of the scale is crowded for about the initial 10 per cent, but above that modern scales are very nearly evenly divided, although if required the upper portion may either be expanded or contracted†.

Old instruments of the moving iron type had large hysteresis errors due to the poor electrical quality of iron then available. This resulted in a difference of calibration on different frequencies and appreciable differences on direct current. Sometimes four calibrations could be obtained on direct current by using increasing and decreasing values

Fig. 9.—A typical 3½ inch flush pattern moving iron instrument.

of current, and then by reversing the polarity and repeating the measurements. Present-day instruments are mainly free from this, more especially if they use one of the nickel-iron alloys now available. In these alloys the permeability in weak fields is very high and the area of the B/H loop is very small, resulting in equal calibrations for a.c. of different commercial frequencies, and for d.c. of either polarity, with both ascending or descending values of current. Another improvement has been the removal of metal parts from the vicinity of the coil. On a.c., such metal carried eddy currents and even formed a closed loop and so become a short-circuited secondary winding, causing quite appreciable errors.

Better quality iron now being available for this purpose, attempts are being made to make more use of it by providing a nearly closed iron circuit, thereby reducing the reluctance of the magnetic path. Whilst this is not yet general practice, it is likely to become so, more particularly as one of the chief advantages is that the design of the magnet circuit becomes more amenable to calculation.

If it is required to predetermine the scale of such an instrument or to obtain a given scale by modifying the iron circuit, the following formula is used :—*

$$\text{Torque} = \frac{I^2}{2}\frac{dL}{d\theta}, \text{ or } \frac{dL}{d\theta} = \frac{2T}{I^2}$$

and hence $L - L_o$, the total change of inductance becomes, $2\int_o^\theta \frac{T}{I^2}\,d\theta$

* See Appendix A.
† See Appendix B.

As it is known that for spring control T is proportional to θ, the variation of inductance for a given relation of I and θ can be found and the iron circuit shaped accordingly.

The usual moving iron instrument up to about ten or fifteen years ago was of the switchboard or portable type, measuring 6 or 8 inches in diameter. The consumption was relatively high — 3 to 5 volt-amperes—and a low-range voltmeter thus required considerable current. Modern instruments of equivalent sizes now require only about 1 volt-ampere, while several forms of small instrument are available having a 2½in. scale length, in which the consumption of power is reduced to less than a quarter of a volt-ampere and about a fifth of a watt. Due to this, low range instruments of 5 milliamperes are possible, although the volt-drop for such a range may be too high for many purposes.

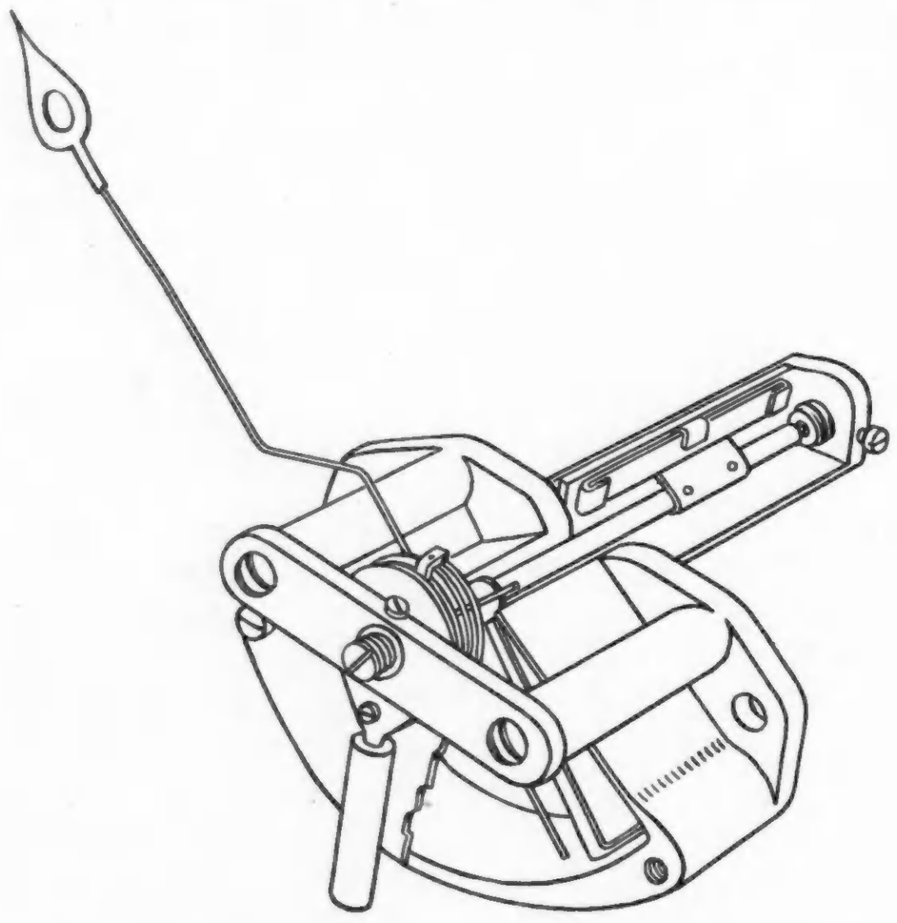

Fig. 10.—Movement of moving iron instrument.

Miniature voltmeters are now made with as low a range as 5 volts quite satisfactorily and for ranges of 100 volts and upwards the current need not exceed 5 milliamperes.

DYNAMOMETER INSTRUMENTS.

The dynamometer embodies what is in effect a moving coil movement in which the permanent magnet has been removed and an electro-magnet substituted. The excitation of this electro-magnet from the same source as the moving coil then renders the instrument suitable for both a.c. and d.c. An air core is usually provided but in some recent designs a core of nickel-iron, having low hysteresis losses, has been introduced, resulting in an increased torque. If the moving and fixed coils carry the same current the instrument becomes an ammeter or voltmeter and the torque is proportional to the square of the current and the rate of change of total inductance (moving and fixed coils). The scale thus has a true square-law calibration. The inductance $L = L_1 + L_2 + 2M$, where L_1 and L_2 are the inductances of the moving and fixed coils and M the mutual inductance between them.

As a wattmeter, where one coil carries line current and the other a current proportional to line voltage, the torque is proportional to the product of these currents and to the rate of change of mutual inductance of the coils from zero to full scale. The resulting scale is thus linear.

Dynamometer instruments are capable of the highest accuracy and are unequalled as wattmeters for precision work. As voltmeters and ammeters they are now little used because modern moving iron instruments have been so much improved and are considerably cheaper.

INDUCTION INSTRUMENTS.

Another electromagnetic instrument is the induction type. This is more or less an induction or Ferraris motor restrained by means of control springs, and hence it operates only on a.c. The stator has coils carrying the current to be measured, and the rotor consists of a light metal disc or cylinder generally made of aluminium.

As the induced e.m.f., and consequently the current flow, depends on the rate of change of flux in the stationary circuit, the current will depend on the frequency of the supply and will be zero with d.c. These instruments, as ammeters, are therefore theoretically correct at only the one frequency, but as voltmeters, they cover a wider frequency range because their series resistance tends to increase the total impedance, of which the resistance component is the larger part. Thus, changes of reactance due to altered frequency have less effect.

The moving element is a disc or a cylinder and the torque applied is independent of the angle of movement, thereby tending to produce continuous rotation, unlike the limited motion of other types of instrument. In induction indicating instruments this torque is restrained by a spring, but the same movement is employed in house service meters, in which the rotation is continuous, affording a means of integrating with time. With this form of motion, it is easy to design an indicating instrument having a scale arc of 270 to 300 degrees, instead of the 110 to 120 degrees common with other types. Advantage is taken of this feature in designing instruments for switchboard use where visibility from a distance is of importance, but because of this, it must not be supposed that such an instrument is more accurate than a moving iron instrument of the same dimensions

merely because the scale is longer. Accuracy depends on the inherent accuracy of the type of movement, its design and manufacture, on the continual constancy of the restraining springs and the accuracy with which the scale may be read.

The only justification for the long scale in this instrument is its "readability" from a distance, a useful feature for switchboard instruments intended for distant observation where the angle of the pointer is noted rather than the actual scale reading.

THERMAL INSTRUMENTS.

Among thermal instruments, the hot-wire pattern is the oldest example. The movement of the pointer in this form of meter results from the expansion of a wire due to the heating effect of the current passing through it. At one time this type of instrument was one of the commonest used for alternating current switchboard work, but it is now entirely supplanted for this purpose by moving iron instruments. The great advantage of thermal instruments is that as the readings are proportional to the square of the current true r.m.s. valves are obtained. The readings obtained are free from errors due to the use of iron, and are accurate for all frequencies and wave-forms.

On the other hand, the heated wires operate very near the elastic limit and the fusing current, and are therefore liable to burn out easily.

Hot wire instruments are now seldom used except as radio current indicators as their accuracy is less than that obtained with the thermo-e.m.f. type. They also usually suffer from insufficient compensation for ambient temperature, which result in a wandering zero, rendering frequent re-setting necessary.

The modern thermal instrument is of the thermo-e.m.f. type in which use is made of the principle that a junction of dissimilar metals when heated, develops an e.m.f. This e.m.f. is proportional to the heat input, and therefore to the square of the current used to heat the junction. The current may be carried by a wire near or in contact with the junction. When the thermo-couple circuit is closed a current flows through a moving coil movement which indicates directly the induced e.m.f. and indirectly the current in the heater.

As with the hot-wire type the reading is independent of frequency and wave-form and the instrument is of great use for all frequencies above those for which other types are unsuitable.

Overload capacity is usually small, however, as the heater wire becomes very hot with full-scale current; its use is therefore restricted to high frequencies or circuits of bad or unknown wave-form where the true r.m.s. reading is required. The high torque of the moving coil movement is utilised as far as possible, but, owing to the limited output from the thermo-couple, the torque is generally less than that obtained in a corresponding size of d.c. instrument. Two or more thermo-couples are sometimes connected in series to increase the torque.

As voltmeters the frequency range over which these instruments may be used is less wide, as it is not practicable to provide a resistance sufficiently non-reactive for use on high frequencies.

Thermo-couples have long been used for laboratory measurements of current but it is only within recent years that self-contained thermo-e.m.f. instruments have been available. The arrangement adopted consists of a heater in the form of a wire or strip, and one or more thermo-couples of metals, such as iron and eureka, which are spaced well apart on the thermo-electric scale. The junction of the two metals may be either in electrical contact with the heater by means of a direct weld, or may be fixed near to but insulated from it, by a bead of some material which has a high electrical resistivity but a comparatively low thermal resistivity.

Evacuation of the air surrounding the heater affords a somewhat greater output from the thermo-couple for a given power (I^2R) in the heater and in instruments with ranges of less than about an ampere this modification is usual.

A more recent type of thermal instrument makes use of the differential expansion of two different metals in the form of a bi-metallic strip. The strip is heated by the line current, either directly by conduction or indirectly by radiation, and the resulting deformation of the strip operates the pointer. The mechanism required is very simple and the cost of manufacture low. One peculiarity is that there is a considerable time delay in operation which may vary from seconds to minutes, depending on the design. This delay is made use of in a type of maximum demand ammeter where short-time overloads are not required to be shown. An auxiliary index pointer is added which shows the maximum reading attained.

ELECTROSTATIC INSTRUMENTS.

Electrostatic instruments depend on the principle that electrodes of like polarity mutually repel each other, while those of unlike polarity attract.

The attraction of like polarities is generally used for both low and high range instruments, but with a difference in the method of application. For a given torque, the lower the voltage the greater must be the change of capacitance between full scale deflection and zero. Usually a system of fixed plates or inductors forms one electrode and a somewhat similar but lighter system forms the moving element which is pivoted so as to rotate in the spaces between the fixed inductors.

High range instruments require a lower total capacitance and therefore have fewer vanes and

fixed inductors with a correspondingly greater separation between opposite poles.

The quadrant electrometer is an early form of this type of meter and embodies two sets of fixed and one set of moving inductors. At zero the moving system is nearly but not wholly within one set of inductors. On applying a voltage v between the two sets of fixed inductors and a voltage V

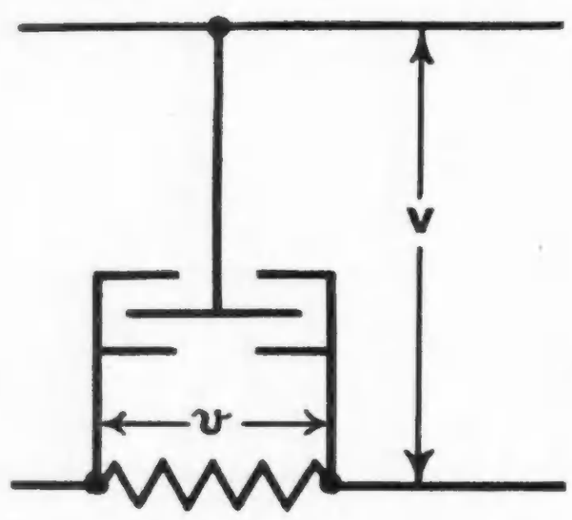

Fig. 11.—Connections of a quadrant electrometer to read power.

between the moving and one of the fixed inductors, the resulting torque causes deflection of the moving set from one set of inductors to the other. As the torque is proportional to vV the instrument may be connected to read power by obtaining v from a shunt carrying line current, and V from the line voltage, or a portion of it. A circuit diagram of this arrangement is shown in fig. 11, although for measurements of low powers and at low power factors, the loss of power in the shunt providing the voltage v has to be taken into account. In addition to the use of the electrometer as a wattmeter, it may also be used to measure a low voltage v by applying a known voltage V. As a voltmeter it is usual to omit one set of inductors, fig. 12, thereby obtaining a two-terminal instrument in which torque is proportional to V^2. The instrument thus gives a square law reading and is suitable for both d.c. and a.c. The torque expression is $T = \frac{V^2}{2}\frac{dC}{d\theta}$, where dC is the change of capacitance for a corresponding change of angle $d\theta$. From this expression will be seen the origin of the square law based on V^2 (or vV) and the necessity for a high rate of change of capacitance.

To increase the capacitance of these instruments, the use of a liquid having a high permittivity has been proposed. The use of these liquids, however, is generally unsatisfactory on account of the relatively low resistivity of high-permittivity liquids and the undesirable physical effects obtained, such as surface tension. Liquids are therefore employed only for some high voltage instruments where the use of transformer oils having a high dielectric strength enables clearances to be reduced and leads to compactness in design.

The torque expression also shows that the torque involves voltage alone and is independent of current. With direct current, however, there is a small initial charging current, and with alternating current, a small wattless current which is proportional to the frequency. In each case no power

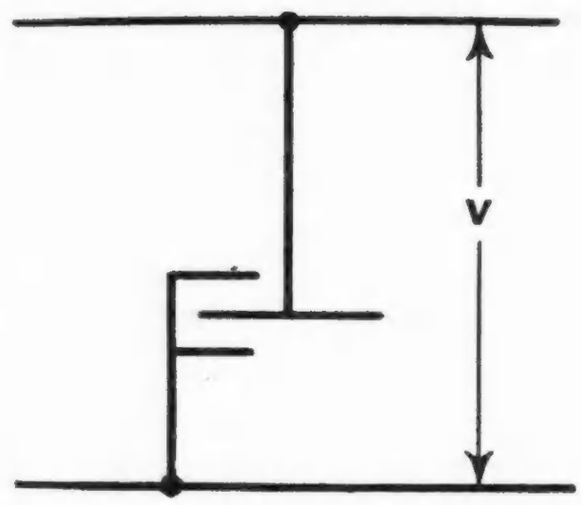

Fig. 12.—Connections altered to read volts.

is absorbed. In the case of a.c., the current leads the voltage by 90°, while with d.c. energy is absorbed initially to an amount V^2/C, of which half is spent in charging the condenser and half in stressing the control. Theoretically this energy would be returned on switching off the supply, but due to leakage it is only possible to obtain energy from a disconnected voltmeter for a very short time after the removal of the charge.

Fig. 13.—Electrostatic voltmeter with series condenser for high ranges.

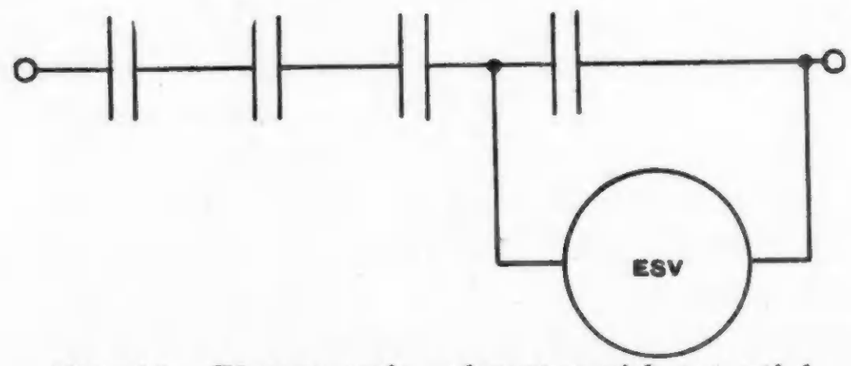

Fig. 14.—Electrostatic voltmeter with potential divider capacitive.

High-range electrostatic voltmeters commonly depart from the electrometer construction and consist of two opposing plates, one fixed and one movable, fig. 15. The application of a voltage to the condenser thus formed leads to the attraction of the plates, a motion which can be translated into a torque by suitable mechanism, imparting a rotary motion to a pointer. Such an instrument is simple in construction and is suitable for measuring voltages up to about one million.

The electrostatic voltmeter is less used to-day than formerly, owing to the improvements which have been made in other types of instrument. In voltage measurements at high pressures, however, it has definite spheres of use, particularly owing to the absence of power consumption which renders it very suitable for measurements of e.m.f. where any current taken by the voltmeter would upset the circuit conditions.

In practice, the torque is generally lower than is possible with other types and owing to its square-law reading it is impracticable to construct a robust instrument having a very low range, although the square-law scale can be modified by suitably shaping the vanes and/or inductors.

These instruments read equally well on d.c. and a.c., which is a valuable feature, as is also their independence of waveform. Frequency error is absent except that at high frequencies the capacitance of the instrument may be of the same order as the capacitance of the circuit, thus altering the circuit constants. Fig. 12 shows how the voltmeter differs from the wattmeter in having only two terminals and one applied voltage.

For high voltage measurement, both d.c. and a.c., the electrostatic voltmeter is of great use. No current is passed on d.c., and no series resistance is therefore required as with other types of voltmeter, involving considerable economy where instruments are constructed to read up to several kilovolts. On a.c. its range may be increased either by series

Fig. 15.—High range electrostatic voltmeter.

condensers of low capacitance (fig. 13) or by a capacitive potential divider (fig. 14). The scale shape is not so good as that of a moving coil or a moving iron instrument and this forms a drawback to its use for test purposes.

Research carried out on pivots and jewels, mentioned previously, has been of considerable value in the production of low-range electrostatic voltmeters where the torque is low. In this connection, it will be appreciated that if a given range is to be halved and the capacitance maintained constant, the torque is reduced to a quarter, but if

Fig. 16.—Sub-standard D.C. test set.

the torque is to be the same, then the change of capacitance must be increased four times and, as this involves a nearly fourfold increase in the weight of the moving system, it is generally impracticable.

ELECTROCHEMICAL INSTRUMENTS.

D.c. ampere-hour meters are the only practical examples of the electrochemical phenomenon as applied to instruments, although in the laboratory, a voltameter is sometimes used as a means of determining current. Quantity is actually directly measured, the reading being an integration of current and time. As d.c. ampere-hour meters, their use has also declined considerably, the mercury motor type being at present employed for this purpose.

MULTI-RANGE AND PORTABLE TESTING INSTRUMENTS.

Some of the instruments described above are eminently suitable for embodying in multi-range and portable testing tests.

For direct current, moving coil instruments have such a low consumption that they may be fitted with series resistances and with shunts for a wide range of voltage and current. In some test sets, one instrument only is used ; other test sets use two,

one for voltage and one for current, giving simultaneous readings.

Moving iron instruments as used in a.c. test sets, will read also on d.c. but with reduced accuracy and with a higher consumption. Their use on d.c. is therefore to be discouraged except where real portability is essential and where a test set for both a.c. and d.c. is required in one instrument.

For a.c. the modern moving iron instrument is now used in test sets of first grade accuracy. The ranges afforded are generally more limited than are those of d.c. test sets having moving coil instruments, the voltmeter giving a fairly wide range, but the ammeter giving one or two ranges only. Ammeters giving higher ranges for a.c. and d.c. require shunts or if intended for a.c. only, require a multi-range transformer.

A test set that is coming into wider use is the rectifier type. The good properties and wide ranges covered by the moving coil instrument on d.c.

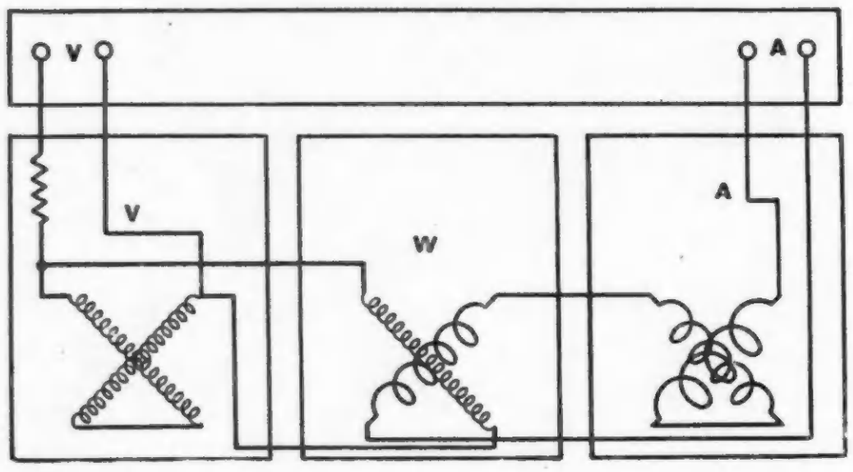

Fig. 17.—Diagram of voltmeter, wattmeter and ammeter test set.

suggest that the addition of a rectifier would afford an accurate instrument for a.c. measurements. Unfortunately, the disadvantage of wave form error is always present. The particular scope of the rectifier instrument has already been described and it has been pointed out that for general power frequency work its use is to be discouraged. Test sets of this type are useful because of their wide voltage ranges, but whilst readings on the high ranges are reasonably accurate, as they are usually obtained on mains supplies having a good wave-form, readings on the lower ranges are generally obtained with supplies fed from transformers or other electromagnetic apparatus, where the wave-form distortion is serious.

These instruments are sometimes used for measuring valve filament voltages but if it is realised that the life of a filament is altered by about 5 per cent for every 1 per cent change in voltage from the rated value, it will be seen that if reliance be placed on the accuracy of a rectifier test set the filament may be so overrun that its life is considerably reduced.

The test sets under discussion are very convenient as indicators, but should not be relied on for accuracies better than 5—10 per cent except for ranges where the supply is known to be free from wave-form distortion and of such low impedance that it is unlikely to be influenced by the rectifier.

Where test sets are required for a.c. power the dynamometer wattmeter is almost universally used for this purpose. Frequently a complete a.c. test set comprises a voltmeter, an ammeter and a wattmeter. The two former may be of the moving iron or dynamometer type, provided with either transformers and resistances or shunts, whilst the wattmeter is always a dynamometer. Triple test sets, such as these, are necessary where a complete a.c. measurement is to be made. Sometimes the connections are simplified by permanently connecting the voltmeter in series or in parallel with the volt circuit of the wattmeter, and similarly with the ammeter and current circuit. Fig. 17 shows such an arrangement. One or more voltage ranges may be provided, whilst the current side is operated directly from a current transformer outside the test set.

For power measurements on polyphase unbalanced load systems a double or triple-element wattmeter is connected to each phase. The two or three elements are carried on one spindle and the readings are in this way added algebraically by mechanical means.

THE TREND OF DESIGN.

Some years ago almost all instruments had either large round dials and were used for switchboards, or were made in portable form, enclosed in carrying cases, the width or diameter being from about 6 to 9 inches.

The general tendency is towards the production of smaller instruments for all purposes. A notable example is the recent development of miniature instruments of about $2\frac{1}{2}$ inches diameter. Demand for small instruments of this type was stimulated first by war-time needs for radio sets and aeroplanes, and since by numerous other applications and economic considerations. This continued demand resulted in considerable research work being carried out, so that now the performance of these smaller instruments is often superior to that of their larger prototypes.

Owing to the convenience of electrical methods of measuring and the possibility of using electrical instruments at a distance, they are used for many indirect measurements of many kinds, such as the measurement of speed, temperature, noise, liquid and gas flow, water level, depth of buried objects, depth of sea, time (by synchronous clocks) water purity, colour density, thickness of metals, small durations of time and illumination values.

This growth in the use of indirect electrical methods of measuring quantities is necessitating

the design of instruments in a form suitable for operation by relatively unskilled operators. Whilst there is still a demand for large switchboard instruments, the tendency towards centralisation of control has developed control desks in which a large number of miniature instruments of $2\frac{1}{2}$ and $3\frac{1}{4}$ inches in diameter are used, together with those of an intermediate size of 4 or 5 inches.

There has been an attempt to popularise the square pattern instrument for switchboard use, but so far little progress has been made in this country.

APPENDICES.

A—EXPRESSIONS FOR TORQUE.

Whilst for most of the types of instrument it is not practicable to mark the scale by calculation, a study of the fundamental expressions for torque is of value. It will be found that the torque is proportional either to the current or the square of the current, except in the case of electrostatic voltmeters ; this determines whether the "fundamental" scale shape shall be of the linear or square-law type. By a linear law is meant one in which the deflection is proportional to the quantity, as in the spring balance or thermometer, while a square-law scale is one in which the deflection is proportional to the square of the quantity, so that in such a scale the divisions open progressively. The square-law scale is difficult to read at low values.

The second factor in the torque expression is that of rate of change of inductance (in electromagnetic instruments) and capacitance (in electrostatic instruments) with deflection.

The following table shows these relations simply.

Type of Instrument	Torque expression	Symbols
Moving coil and polarised moving iron.	$I\frac{dN}{d\theta}$	N = linkages = line-turns, or the product of magnetic lines and turns on the coil. θ is the angle of deflection.
Moving iron, dynamometer and induction, voltmeter and ammeter.	$\frac{I^2}{2}\frac{dL}{d\theta}$	L is the inductance of the system.
Dynamometer wattmeter.	$VI\frac{dM}{d\theta}$	M is the mutual inductance between the fixed and moving coils.
Electrostatic voltmeter.	$\frac{V^2}{2}\frac{dC}{d\theta}$	dC is the change of capacitance for a small angle $d\theta$.

B—SCALE SHAPES.

Some typical scale shapes are shown in figs. 18—22.

Fig. 18 is a linear scale used on moving coil instruments and dynamometer wattmeters. Fig. 19 shows a square-law scale as found on all square-law instruments that are not purposely modified in design. It is found generally on the dynamometer voltmeter and ammeter and on thermo-e.m.f. instruments. The half-scale point is $\frac{10}{\sqrt{2}} = 7.07$.

Moving iron instruments almost always use a modified form of the true square-law scale, the most usual type being that shown in fig. 20, where it is attempted to obtain a scale as linear as possible. It will be seen that except for the initial 10 per cent or so a linear scale is obtained. Sometimes a moving iron ammeter is required to have a scale closed at the upper end of the range so that normal loads

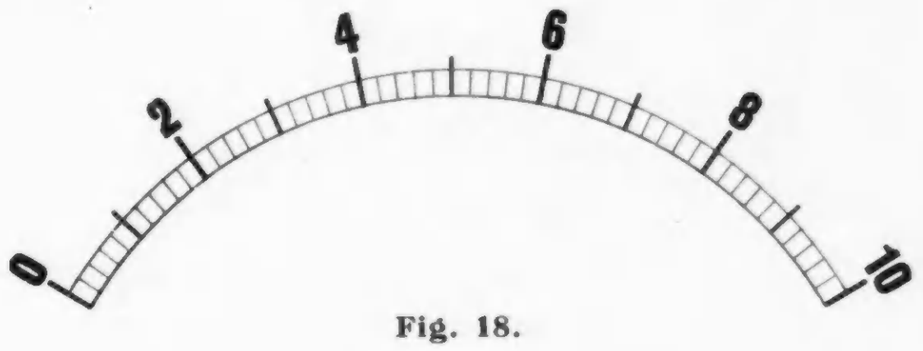

Fig. 18.

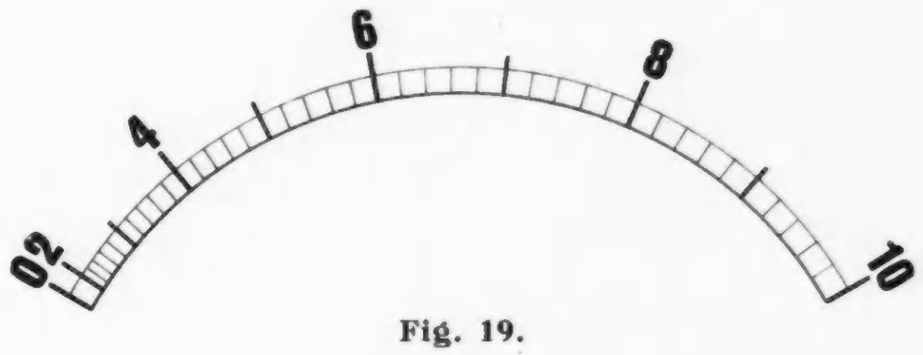

Fig. 19.

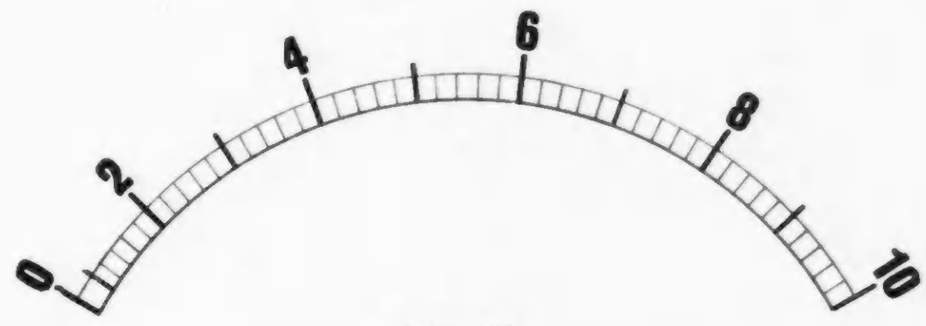

Fig. 20.

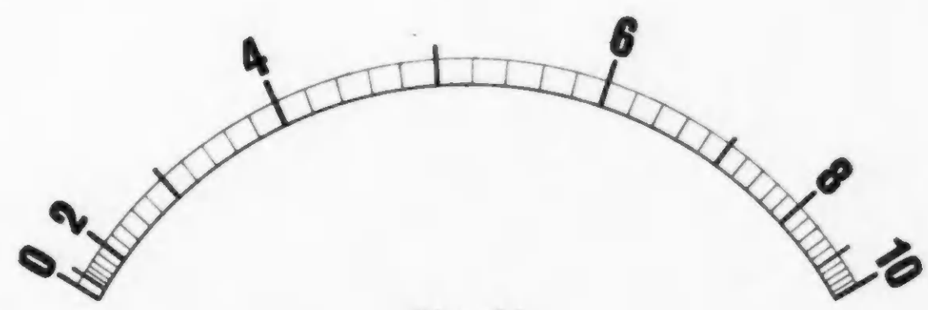

Fig. 21.

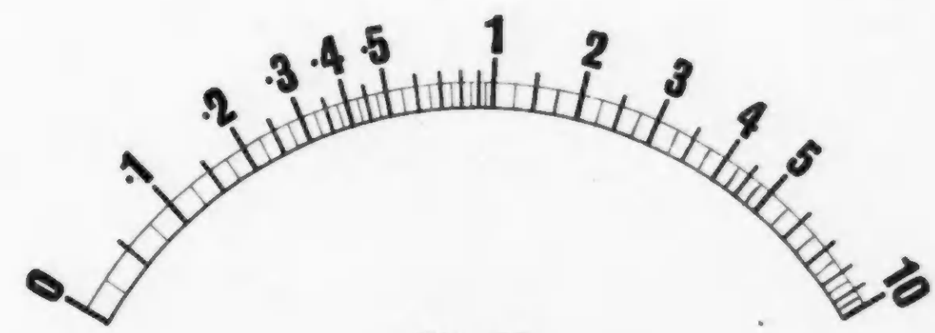

Fig. 22.

are read near the middle of the scale and overloads are shown at the end of the scale. A typical scale of this type is shown in fig. 21.

A further type of scale is the logarithmic scale, which has the advantage of giving equal percentage accuracy at all points. It is less easy to read by unskilled observers, however, and is not obtained naturally in any of the types of instrument described, although in practice it is approached by that of the ohmmeter, an instrument having two coils, somewhat similar to the wattmeter, but connected to read the quotient of volts and amperes instead of the product of these quantities. Even in this instrument however, special design is necessary to obtain the logarithmic scale (fig. 22).

C—MATERIALS.

In addition to the improvements noted, due to the use of cobalt-steels for permanent magnets and nickel-iron for electromagnets, two other classes of material have had an important bearing on design.

One of these comprises moulded plastics, of which the phenol formaldehyde resin, "Bakelite," is a typical example; and the other a series of light alloys suitable to repetition work in die castings and pressings.

Bakelite is now very commonly used for the cases of small switchboard and portable instruments, and it is increasingly used in the internal construction of instruments; also for parts such as damping chambers, coil formers, etc., where a high-insulation material having good mechanical characteristics is required. For damping chambers the excellent smooth finish obtained with bakelite mouldings is of great importance and its importance as a substitute for metal in or near a.c. fields cannot be overestimated in view of the reduction of eddy-current errors it affords.

Die castings and pressings of suitable alloys are replacing hand-turned brass and other alloys and sand castings of various metals. Aluminium-base alloys are naturally light and possess a clean finish with sharp edges, giving a finished product of precise dimensions. Tin-base alloys have a particularly clean, sharp finish which is ideal for small parts.

D—USES OF VARIOUS INSTRUMENTS.

The following table shows in concise form the most suitable instrument for any particular duty.

Use	Instrument	Advantages	Disadvantages
D.C. Volts and Amperes.	1. Moving Coil	Good scale, accurate, wide range.	
	2. Polarised Moving Iron.	Cheap.	Inaccurate. Poor damping.
A.C. Volts and Amperes.	1. Moving Iron.	Cheap, accurate, all power frequencies.	
	2. Induction.	Long scale.	Narrow frequency range. Expensive.
A.C. Power.	1. Dynamometer.	Accurate. Also good for D.C.	
	2. Induction.	Long scale.	Generally less accurate than dynamometer. Narrow frequency range.
A.C. Low Ranges. Low power circuits.	Rectifier.	Low consumption.	Bad wave-form error.
A.C. audio frequency Volts and Amperes.	Rectifier.	Low consumption. Wide frequency range.	Bad wave-form error.
A.C. radio frequency Volts and Amperes.	Thermo-e.m.f.	All frequencies and D.C. No waveform error.	Low overload capacity. Bad scale shape.
D.C. and A.C. High Voltages.	Electrostatic.	Simple and cheap for high ranges. No power consumption.	Scale shape not good.

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